Estimation of High-Resolution Wind Speed From a Spaceborne SAR

Alaska SAR Demonstration

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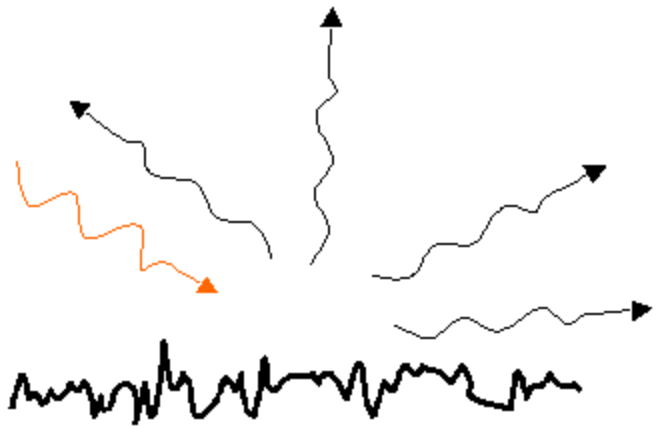
Presentation outline

- Understanding radar scattering from a physical standpoint.
  - Bragg scattering.
- The relationship between radar cross section and wind speed.
  - What do we need to know to estimate wind speed?
- Scheme for estimating wind speed.
- Accessing the data.
- Interpretation of SAR wind speed data.
  - Getting the most from the SAR image and how not to be fooled.

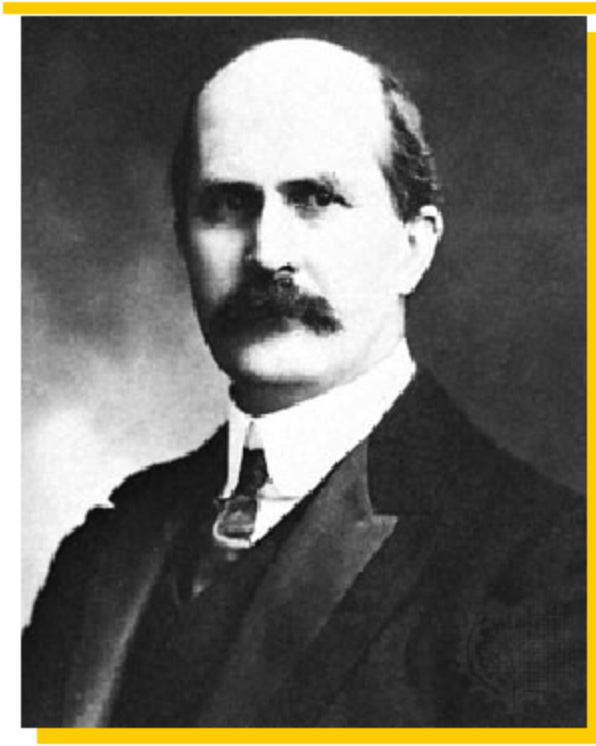
Scattering

Specular scattering from a smooth surface. Most of the energy is reflected away.

Defuse Scattering from a rough surface. Energy is reflected in all directions.



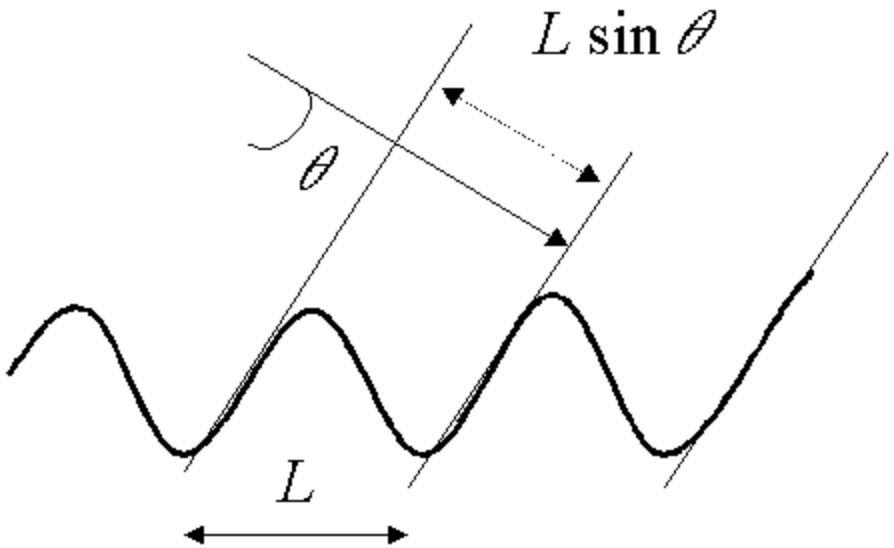
Bragg Scattering



Sir William Lawrence Bragg
Bragg resonance was discovered in the context of scattering from crystal structures.
Encyclopedia Britannica, 1999.

A periodic structure will set up a resonance for waves that match the Bragg condition.

$$\lambda = 2 L \sin\theta$$



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Reasons for surface roughness to change

- Wind Speed
  - As wind speed increases, the height of waves at the Bragg wavelength increases.
- Atmospheric stability
  - For a very stable atmosphere there is less roughness induced by the wind than in a neutral or unstable case.
- Ocean Surface Waves
  - Change local tilt.
  - Long wave-short wave interactions.

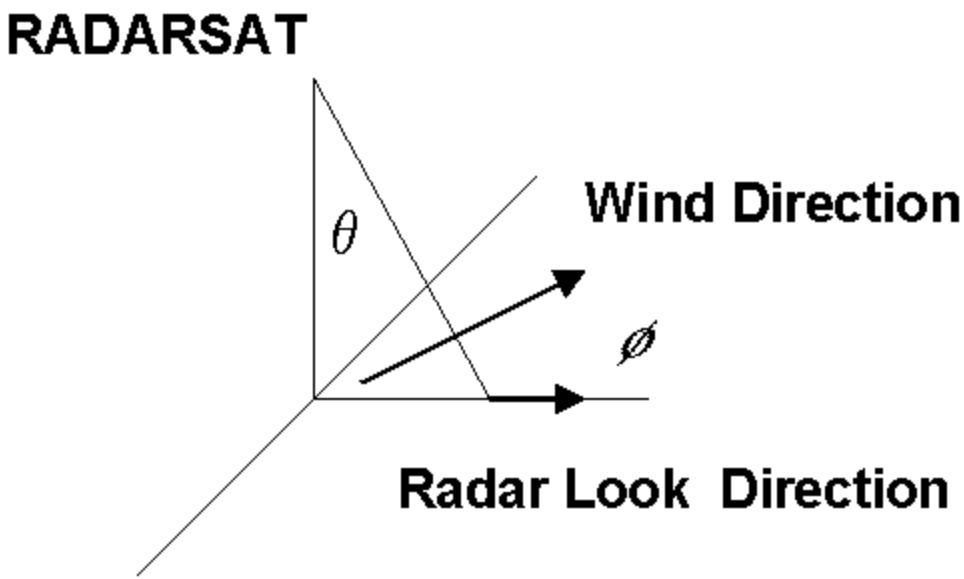
Bragg scattering

- Ocean surface waves with a wavelength that satisfies the Bragg resonance condition will contribute the most to radar cross section.
- Example: RADARSAT, λ = 5 cm, θ = 20° to 46° for ScanSAR mode. The resonant Bragg waves thus vary from 7.3 cm to 3.5 cm in wavelength.
- Whatever changes waves on this scale will change the radar cross section.

Reasons for surface roughness to change

- Currents
  - Surface currents will change the relative speed between the wind and the surface.
- Internal waves
  - Internal waves induce surface currents that can affect the Bragg waves.
  - Internal wave currents can cause certain surfactants to accumulate.
- Surfactants
  - Suppress roughness and Bragg wave generation.

Radar Geometry



General form of the wind speed model function

$$\sigma_0 = a(\theta)U^{\gamma}\,[1 + b(\theta)\cos\phi + c(\theta)\cos 2\phi\,]$$

- σ_0 represents radar cross section.
- U is the wind speed raised to a power γ.
- ϕ is the angle between the wind speed and the radar look direction. If θ is equal to zero then the radar is looking into the wind.
- a, b, c are constants and a function of incidence angle θ.

CMOD4 Model Function

- ERS-1 had a C-band (5 cm wavelength) scatterometer for measuring wind speed.
- Need for an updated function relating wind speed and direction to cross section.
- CMOD4 is the fourth iteration of this model function.
- Based on aircraft measurements over buoys.
- Designed for *vertical* polarization.

CMOD4 Model Function

$$\sigma_0 = a(\theta)U^{\gamma}\left[1 + b(\theta)\cos\phi + c(\theta)\cos 2\phi\right]$$

Nominal functional form

$$\sigma_0^{\mathrm{V}} = a(\theta)f(U)^{\gamma}\left[1 + b(\theta)\cos\phi + c(\theta, U)\cos 2\phi\right]^{1.6}$$

CMOD4

Going from vertical to horizontal polarization

$$\sigma_0^{\mathrm{H}} = \frac{\left(1+\alpha \tan^2\theta\right)^2}{\left(1+2\tan^2\theta\right)^2}\sigma_0^{\mathrm{V}}\left(U,\theta,\phi\right)$$

Where α is a parameter that is still an area of research. Note that when $\theta = 0$, the return from vertical and horizontal polarization is the same.

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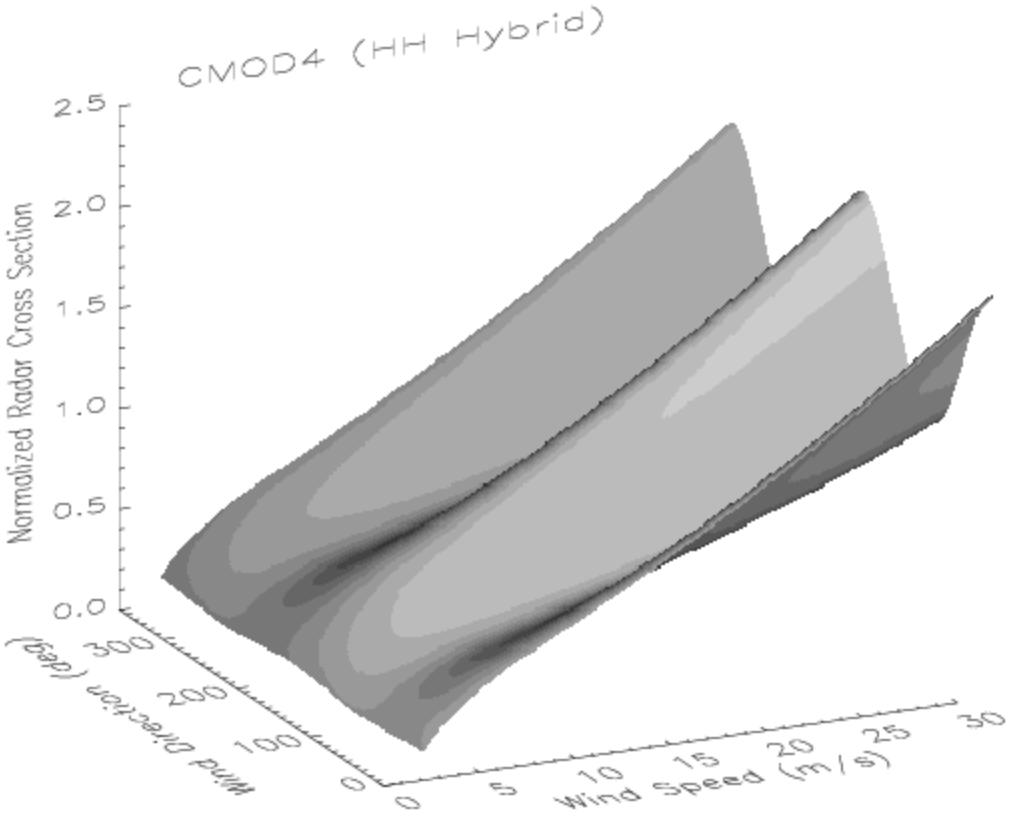
CMOD4 radar cross section at a given incidence angle as a function of wind speed and direction



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A single cross section measurement is not sufficient to infer wind speed

- Given a wind speed and direction, radar incidence angle and radar look direction, we can predict the radar cross section.
- However, from a single measurement of cross section and a particular incidence angle and look angle it is not possible to uniquely determine wind speed and direction. We need additional information.

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Resolving the cross section ambiguity for a scatterometer

- Scatterometers resolve this by looking at the same spot on the ocean from a variety of angles and polarizations.
- The limitation on conventional scatterometers is resolution. At best the resolution is between 25 km and 50 km. This is not adequate in coastal regions.
- It is this limitation that drives the use of wide-swath SAR for wind speeds

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Resolving the cross section ambiguity for SAR

- A conventional SAR makes a measurement of cross section at a single incidence and aspect angle.
- If we had wind *direction* information, we could uniquely estimate wind *speed*.
  - Use the SAR data itself to estimate wind direction.
  - Use independent model estimate of wind direction.

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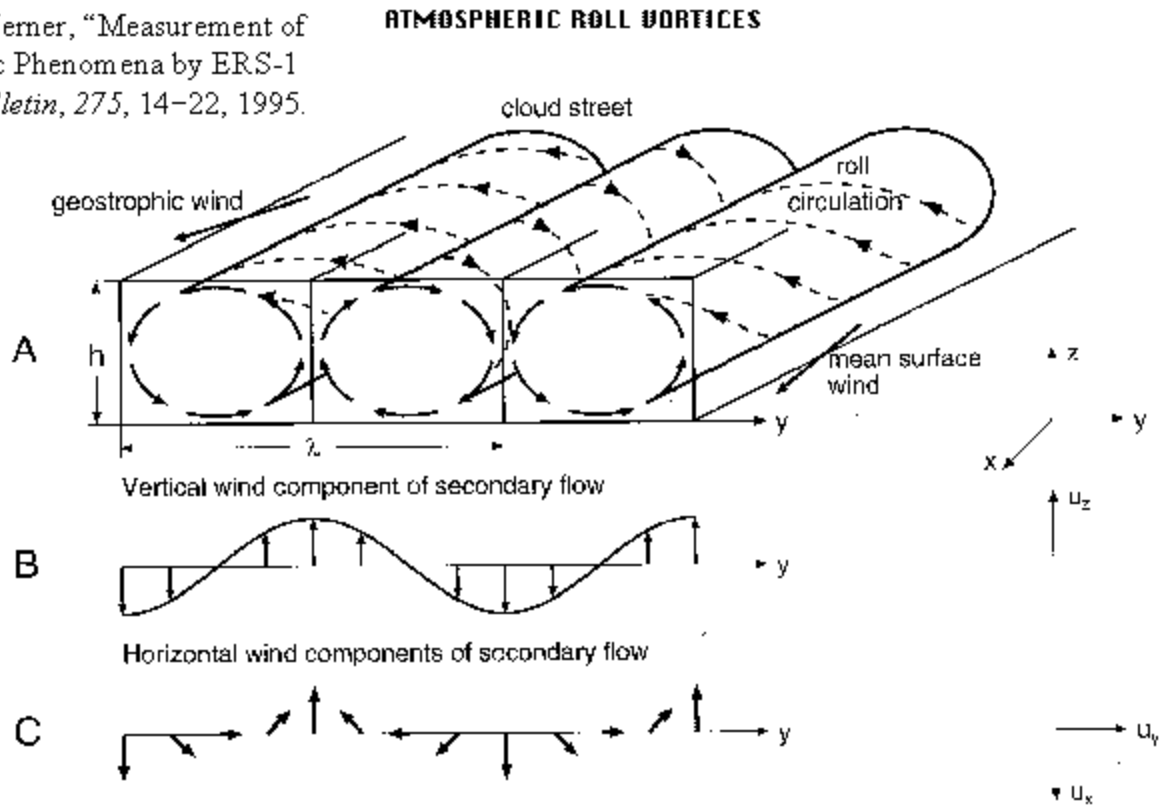
Using the SAR data itself to estimate the direction: wind rows

Adapted from: Alpers, Werner, "Measurement of Oceanic and Atmospheric Phenomena by ERS-1 SAR", *Radio Science Bulletin*, *275*, 14–22, 1995.



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Using the SAR data itself to estimate the direction: advantages and limitations

- Advantages:
  - Able to distinguish small spatial scale changes in wind direction not seen in a model.
  - Not fooled by a slight displacement of a storm in the wind field.
- Limitation:
  - Wind direction signatures not always available.

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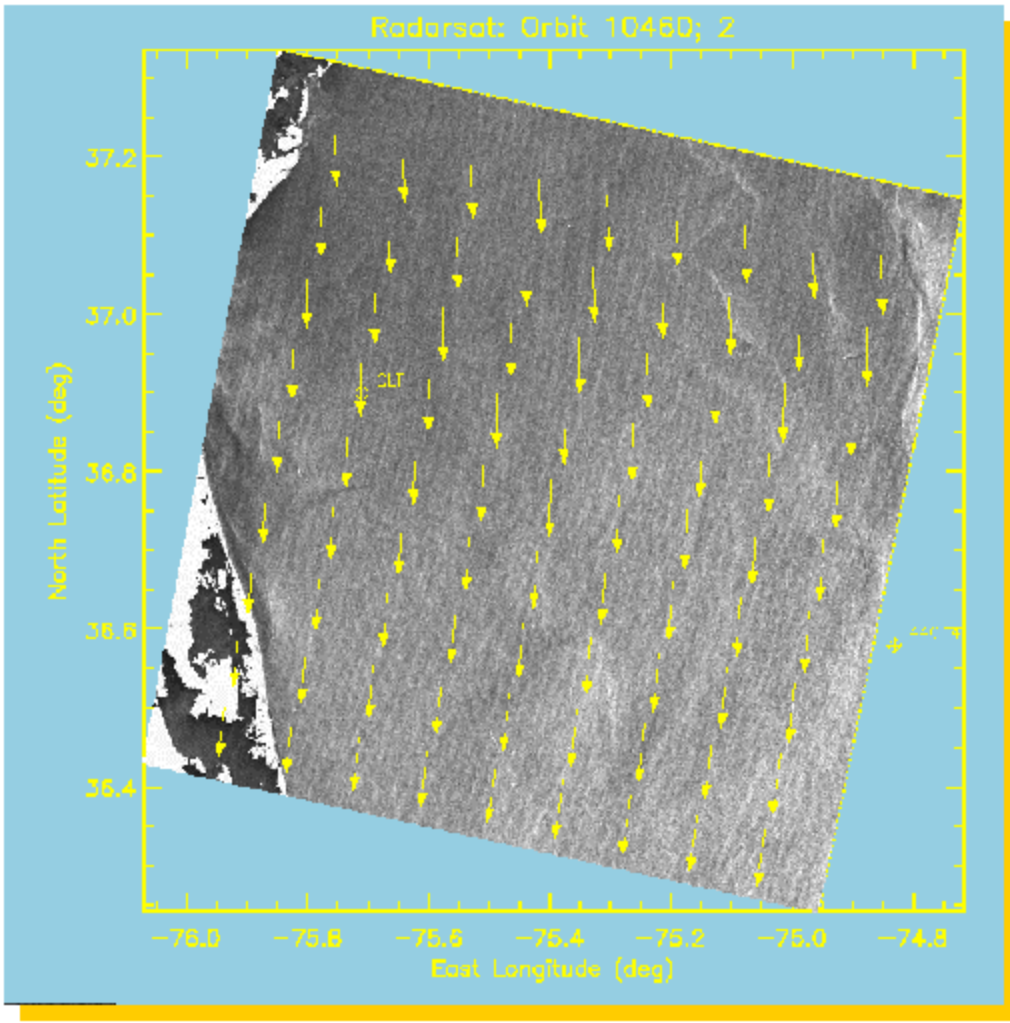
Sample wind row image



This image is from the descending segment of orbit 10460 on 5 November, 1997 at 11:12 GMT. The arrows represent the wind direction estimates from the NOGAPS model.

Adapted from: Thompson and Beal, "Mapping of Mesoscale and Submesoscale Wind Fields Using Synthetic Aperture Radar." *A Symposium on Emerging Coastal and Marine Applications of Wide Swath SAR*, Johns Hopkins University Applied Physics Laboratory, Laurel, MD, March 1999.

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Using a model for wind directions: advantages and limitations

- Advantages:
  - Always available.
  - Always self-consistent.
- Limitations:
  - Misses small scale changes in direction.
  - Possible misplacement of meteorological events.
  - Temporal coincidence may not be perfect.

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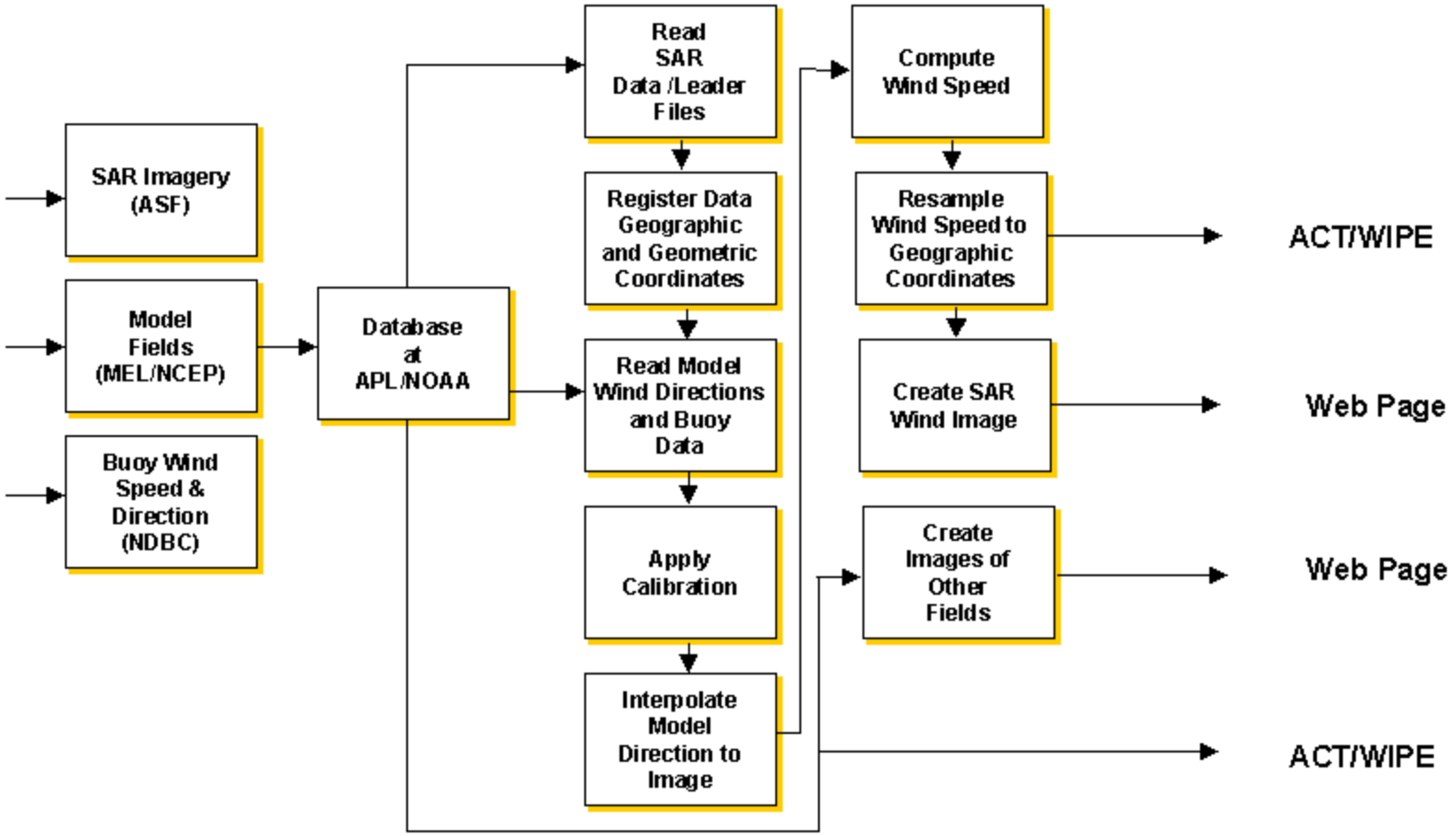
Data flow for estimation of high-resolution wind speed from SAR



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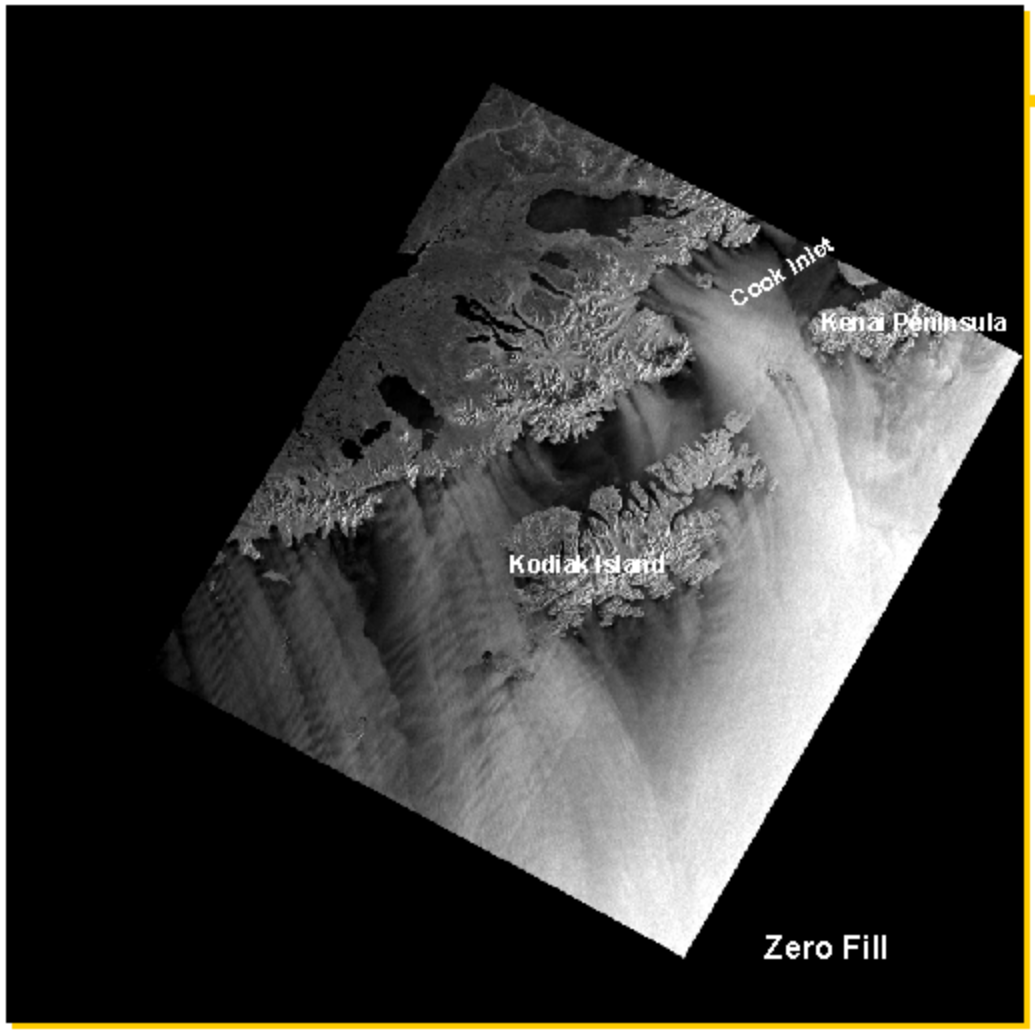
Sample SAR image from ASF (digital number)



Sample image near Cook Inlet and Kodiak Island as processed by ASF. The imagery is in a polar stereographic projection. The intensity of the image is proportional to the byte value. The byte value, in turn, is proportional to image amplitude. This image was acquired on October 6, 1998 at 16:37:44 Z. The image center is 153.9 W 57.6°N

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Sample SAR image from ASF (radar cross section)

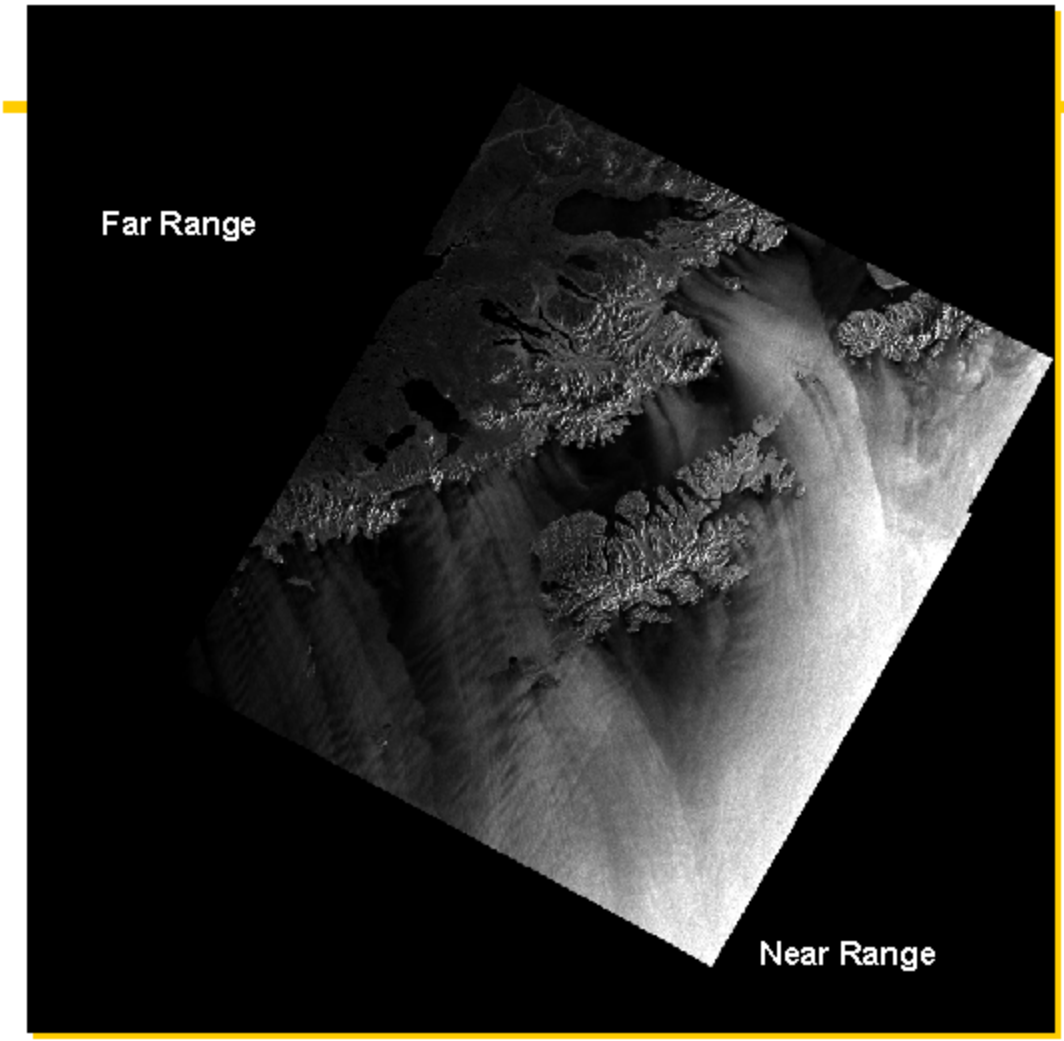

Image brightness is proportional to horizontal polarization radar cross section. There is a rapid falloff in cross section with incidence angle.

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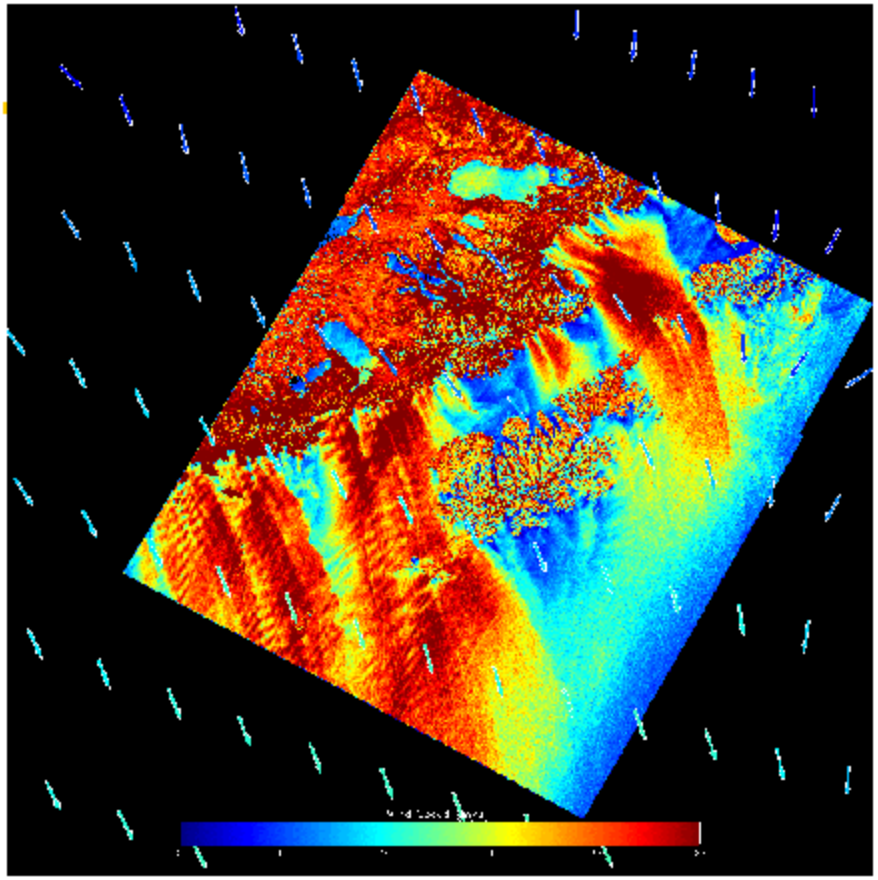
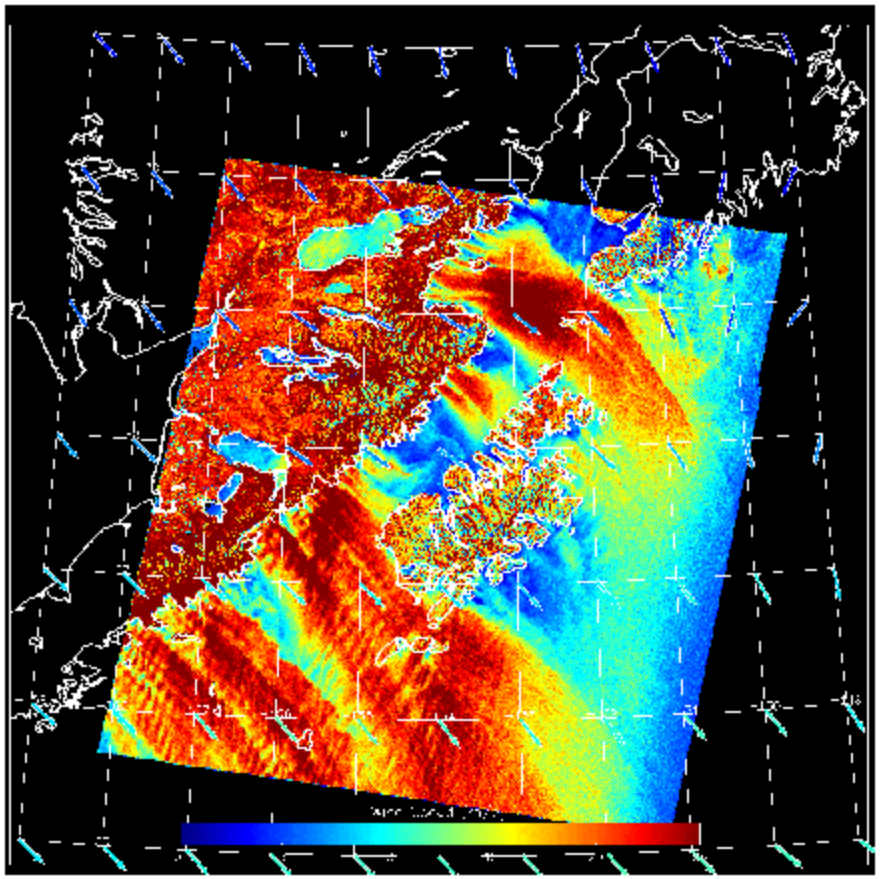
Sample SAR image from ASF (wind speed)



Wind Speed. The maximum wind speed is 25 m/s.



Resampled Wind Speed. The maximum wind speed is 25 m/s.

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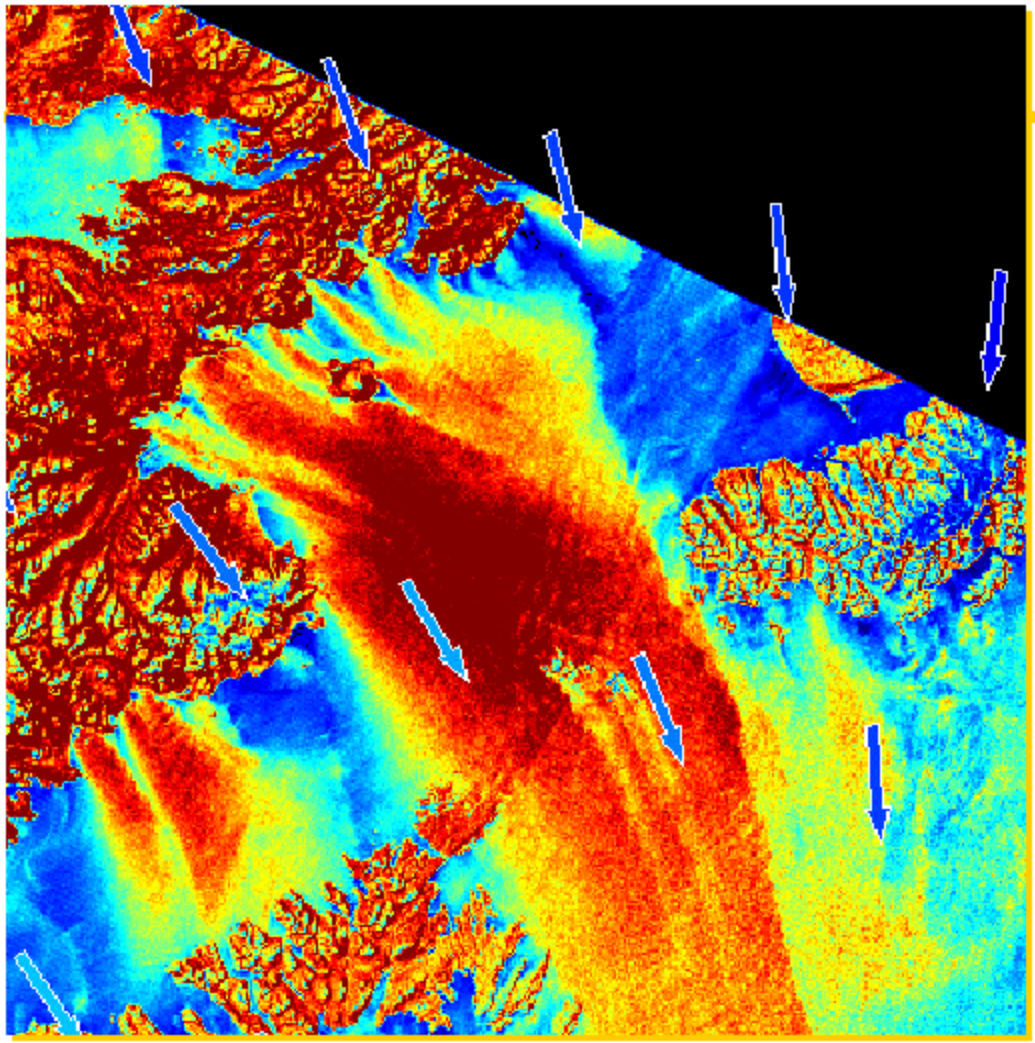
Sample SAR image from ASF (wind speed close up)



Close up of wind speed. The arrows represent the model wind speed. The arrow color is related to wind speed and orientation gives wind direction.

Access to data

- WIPE Software
- Open Web Pages:
  - NOAA/NESDIS
    - Alaska SAR Demo:
      - URL:http://manati.wwb.noaa.gov/orad/experiment_fm.html
    - Direct link to high resolution winds:
      - http://manati.wwb.noaa.gov/sar_pub_5s/AKDEMO_products/APL_winds/
  - JHU/APL
    - http://fermi.jhuapl.edu/sar/stormwatch/gulf_of_alaska/

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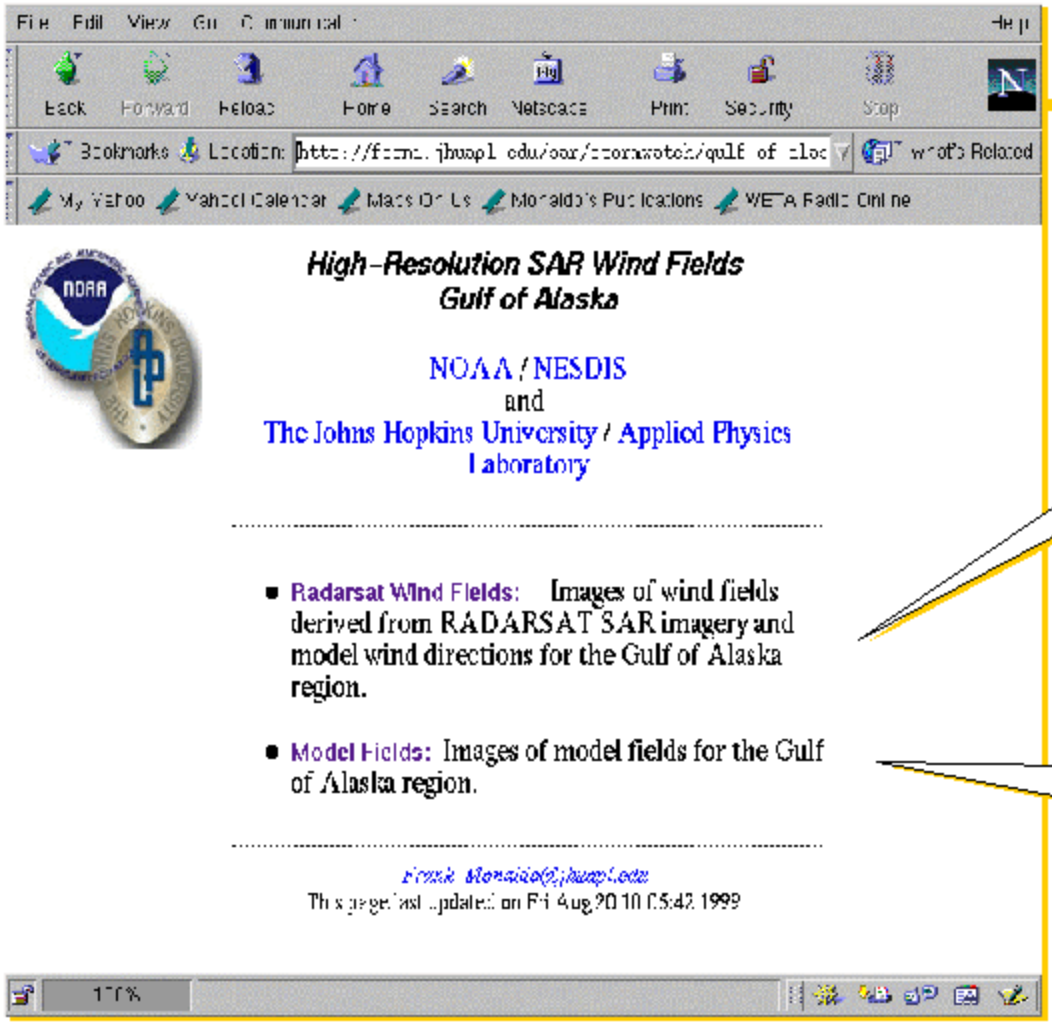
Web page structure: front end



Access to high-resolution wind speed GIF images from the SAR

Access to GIF image of model derived fields

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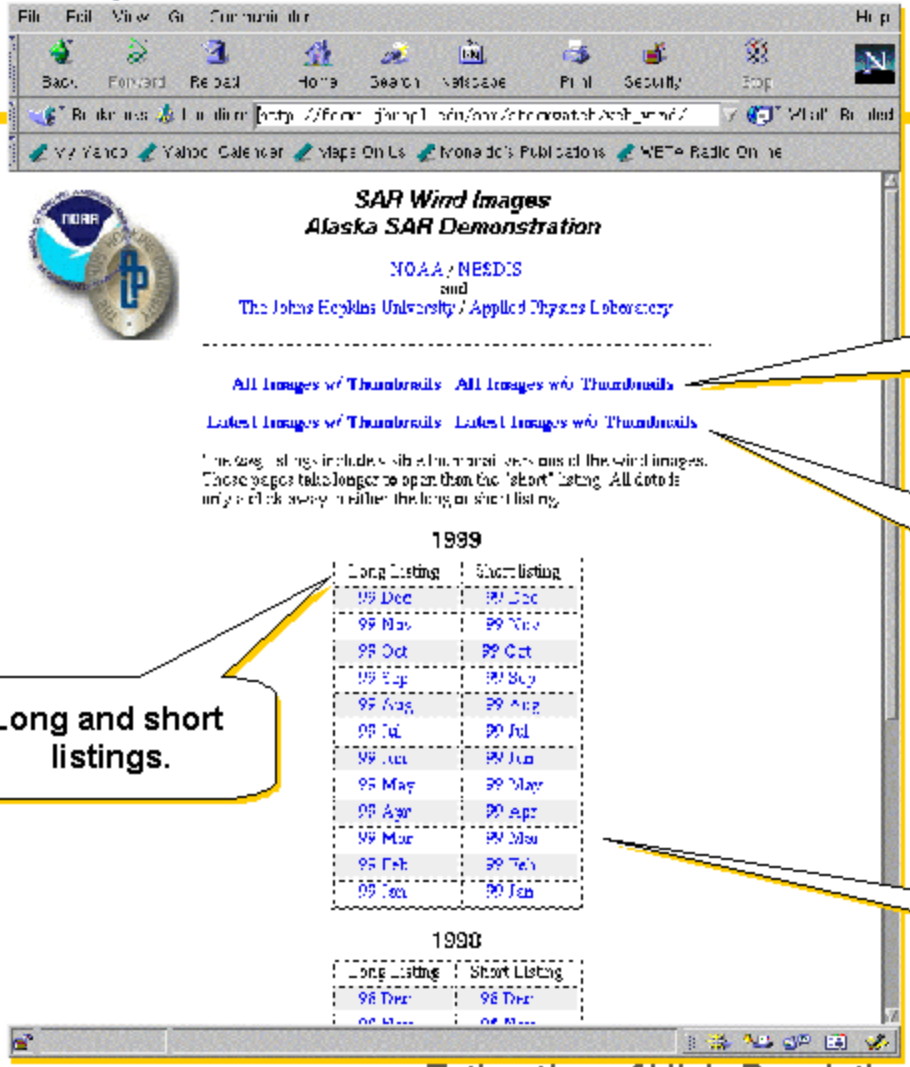
Web page structure: SAR wind speed images



SAR wind images for all images acquired.

Links to monthly listings SAR wind image for the last 15 images acquired.

Long and short listings.

Links to monthly listings SAR wind images.

Web page structure: long/short listings

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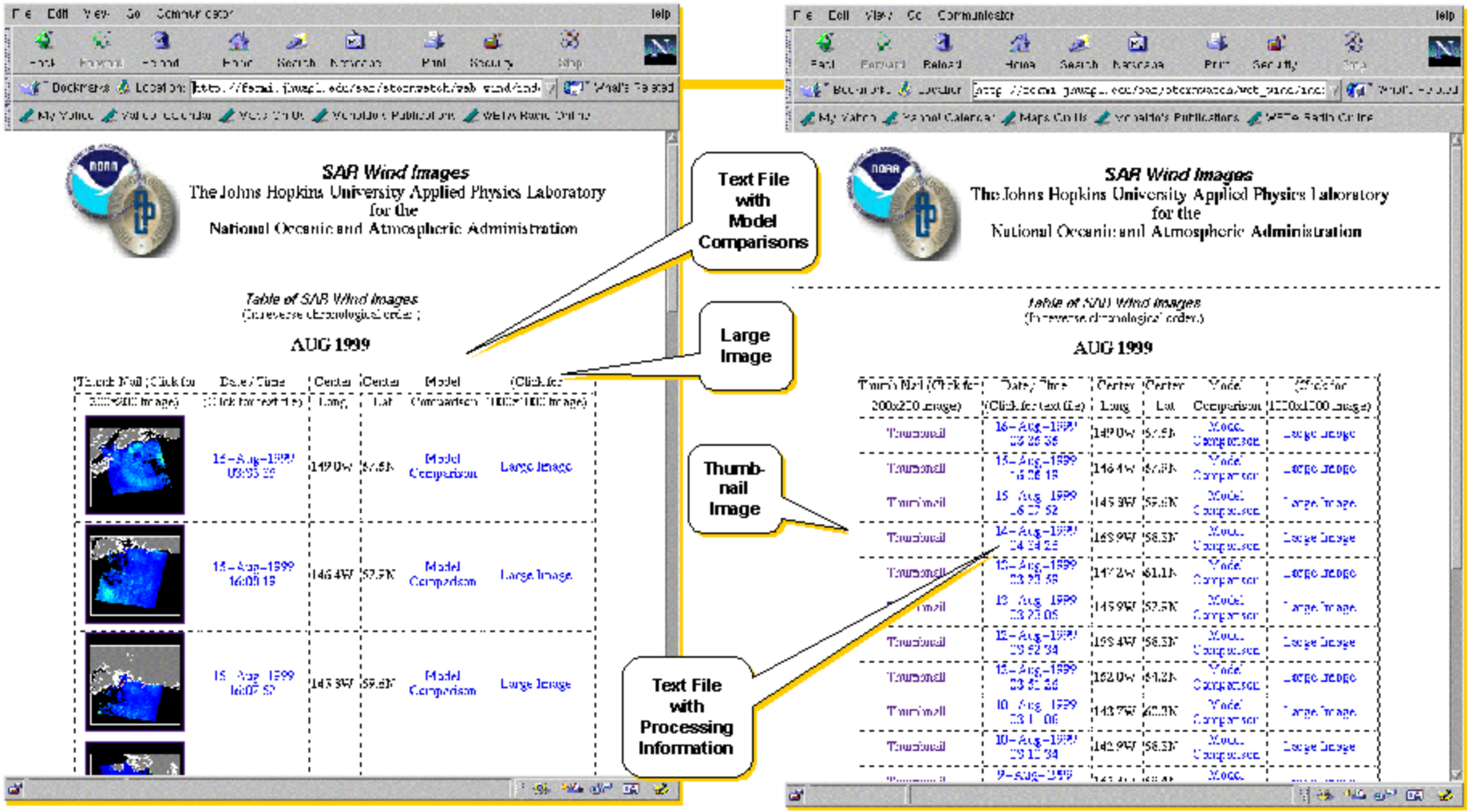

Sample Images

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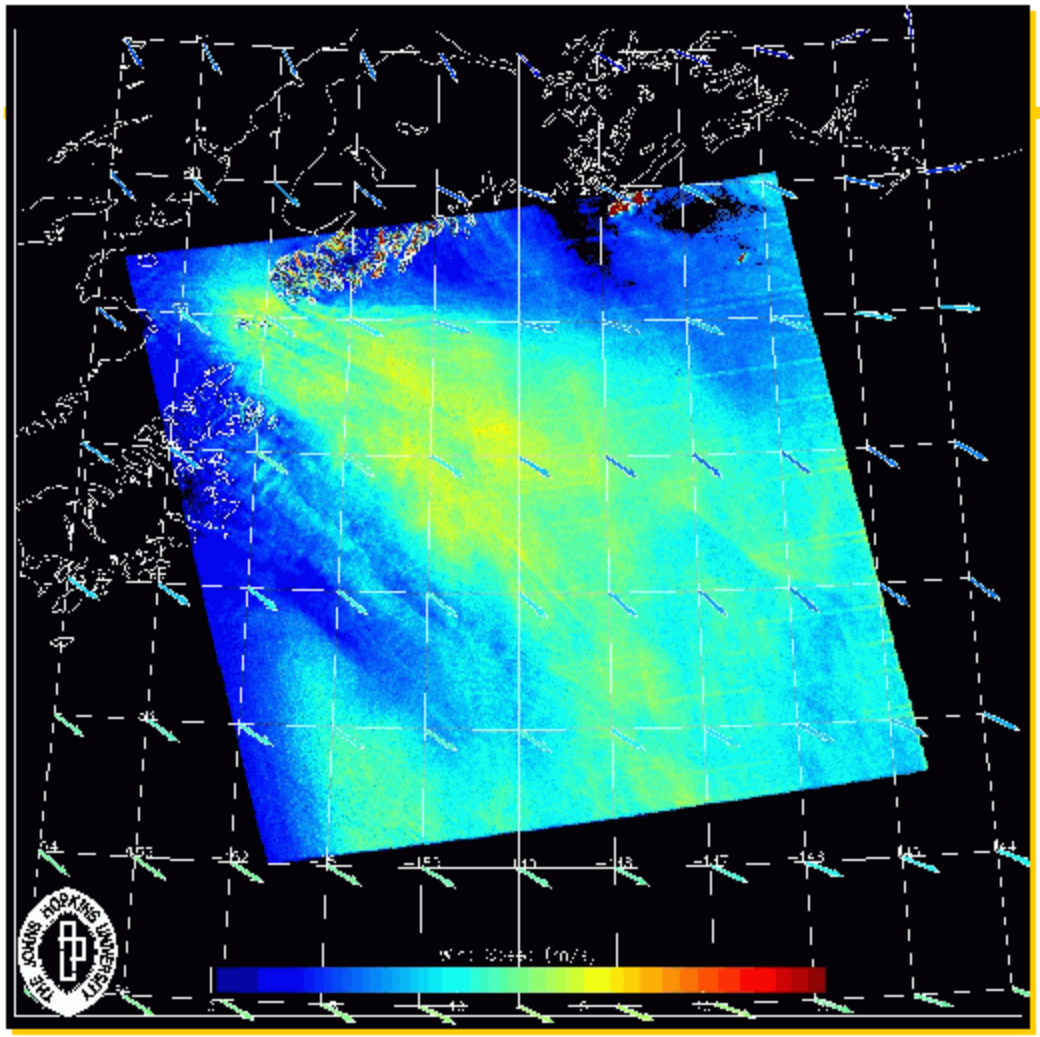

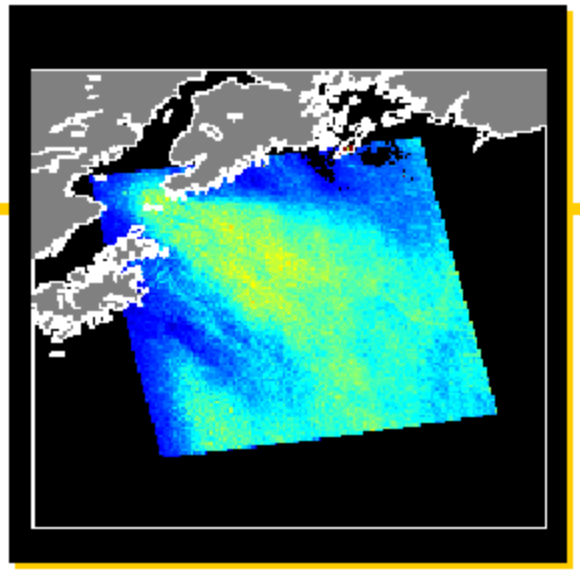

Thumbnails:
- Land mask
- No model information
- 200 x 200 pixels

Large Images:
- No land mask
- Coastlines drawn
- Color-coded model winds
- Color-bar
- Latitude-longitude lines.

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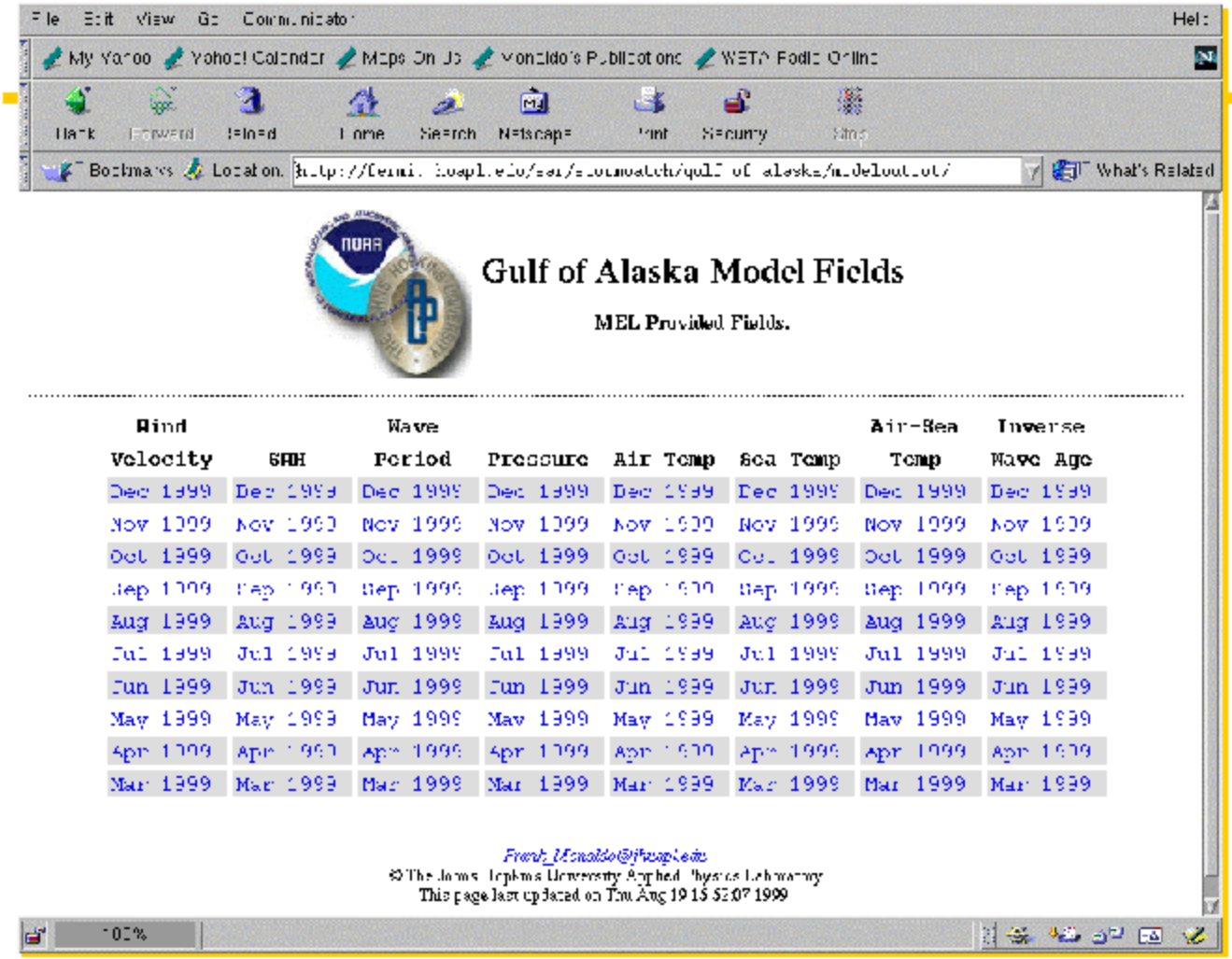
Web page structure: model images



Gulf of Alaska Model Fields

MEL Provided Fields.

Wind Velocity	SWH	Wave Period	Pressure	Air Temp	Sea Temp	Air-Sea Temp	Inverse Wave Age
Dec 1999	Dec 1999	Dec 1999	Dec 1999	Dec 1999	Dec 1999	Dec 1999	Dec 1999
Nov 1999	Nov 1999	Nov 1999	Nov 1999	Nov 1999	Nov 1999	Nov 1999	Nov 1999
Oct 1999	Oct 1999	Oct 1999	Oct 1999	Oct 1999	Oct 1999	Oct 1999	Oct 1999
Sep 1999	Sep 1999	Sep 1999	Sep 1999	Sep 1999	Sep 1999	Sep 1999	Sep 1999
Aug 1999	Aug 1999	Aug 1999	Aug 1999	Aug 1999	Aug 1999	Aug 1999	Aug 1999
Jul 1999	Jul 1999	Jul 1999	Jul 1999	Jul 1999	Jul 1999	Jul 1999	Jul 1999
Jun 1999	Jun 1999	Jun 1999	Jun 1999	Jun 1999	Jun 1999	Jun 1999	Jun 1999
May 1999	May 1999	May 1999	May 1999	May 1999	May 1999	May 1999	May 1999
Apr 1999	Apr 1999	Apr 1999	Apr 1999	Apr 1999	Apr 1999	Apr 1999	Apr 1999
Mar 1999	Mar 1999	Mar 1999	Mar 1999	Mar 1999	Mar 1999	Mar 1999	Mar 1999

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This page last updated on Tue Aug 10 15:52:07 1999

Model Fields for the Gulf of Alaska and Northern Pacific region listed by month and physical field.

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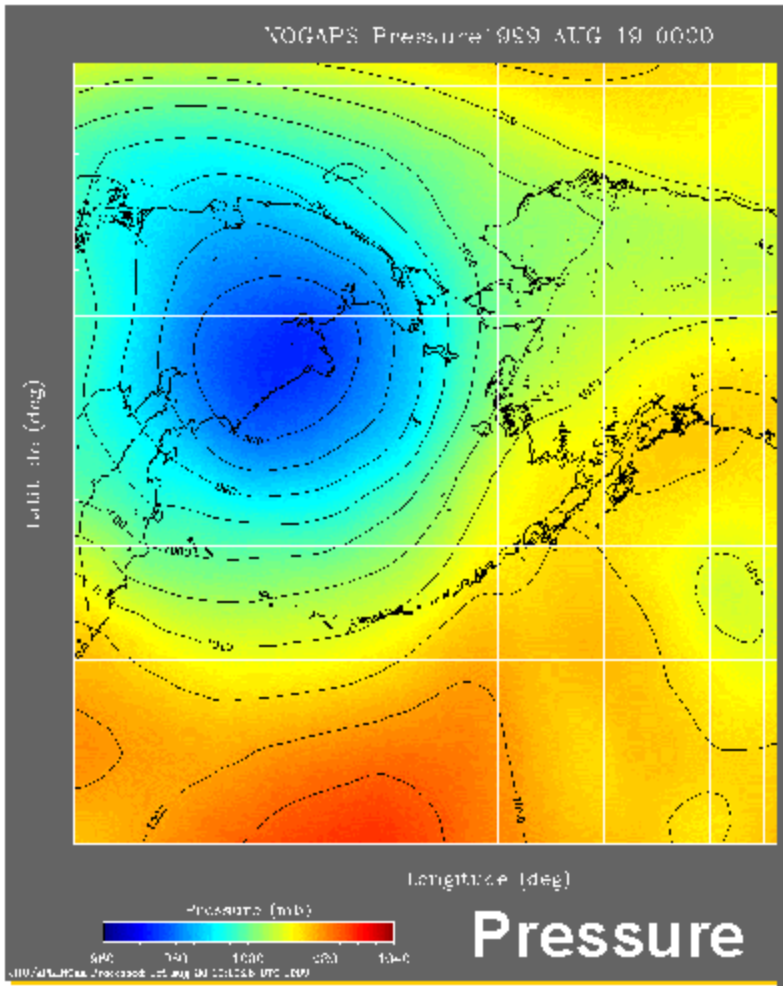
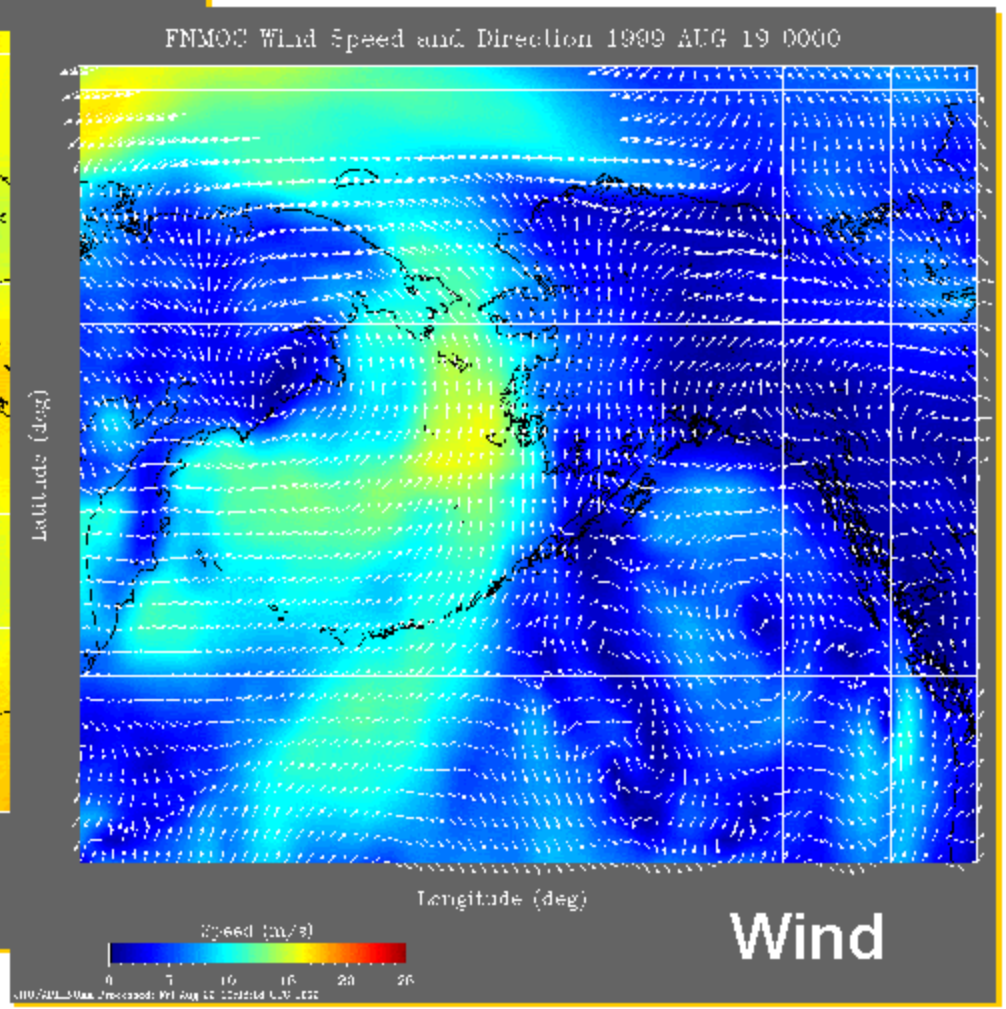
Model images: pressure and wind





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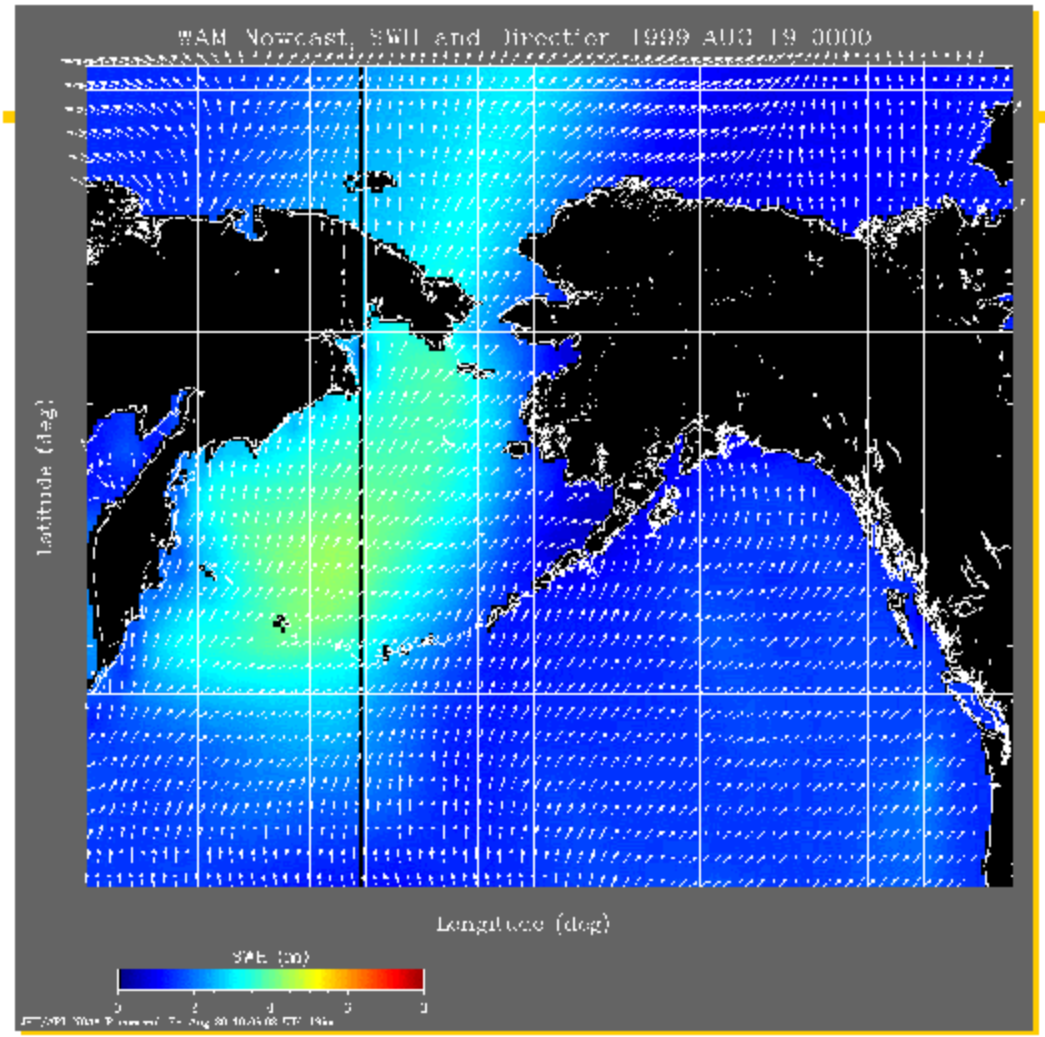
Model images: waves



Significant Wave Height and Dominant Direction

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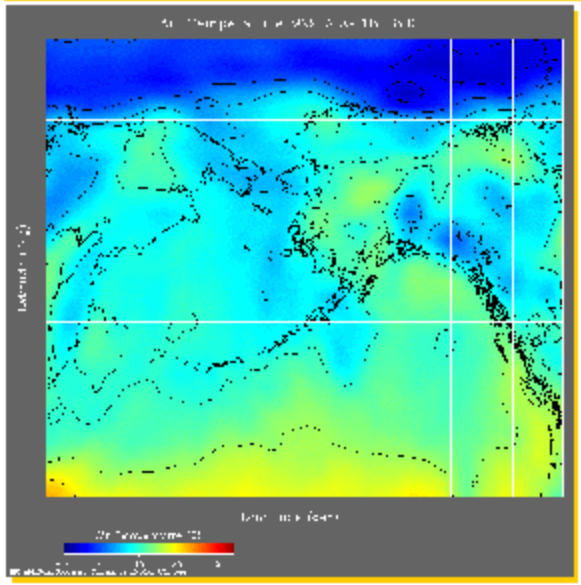
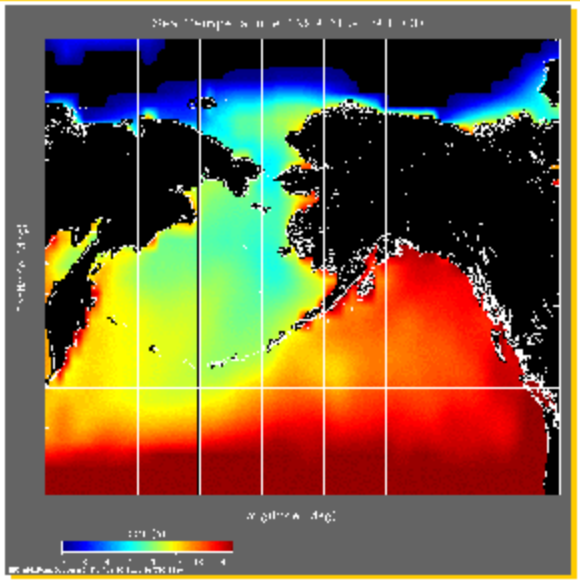
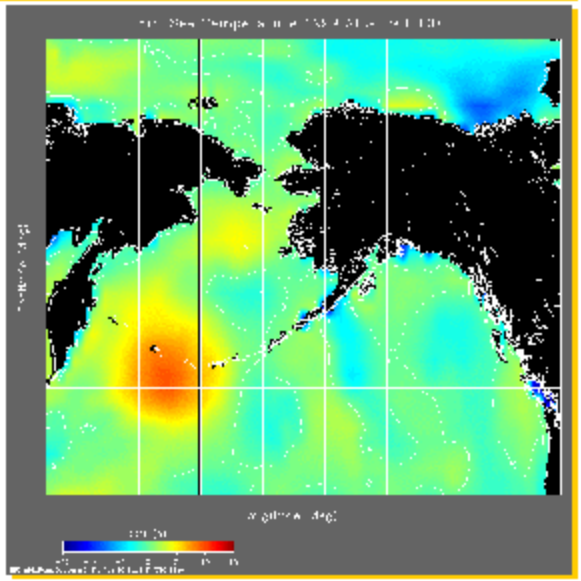
Model images: temperature



Air Temperature



Sea Temperature



Air - Sea Temperature

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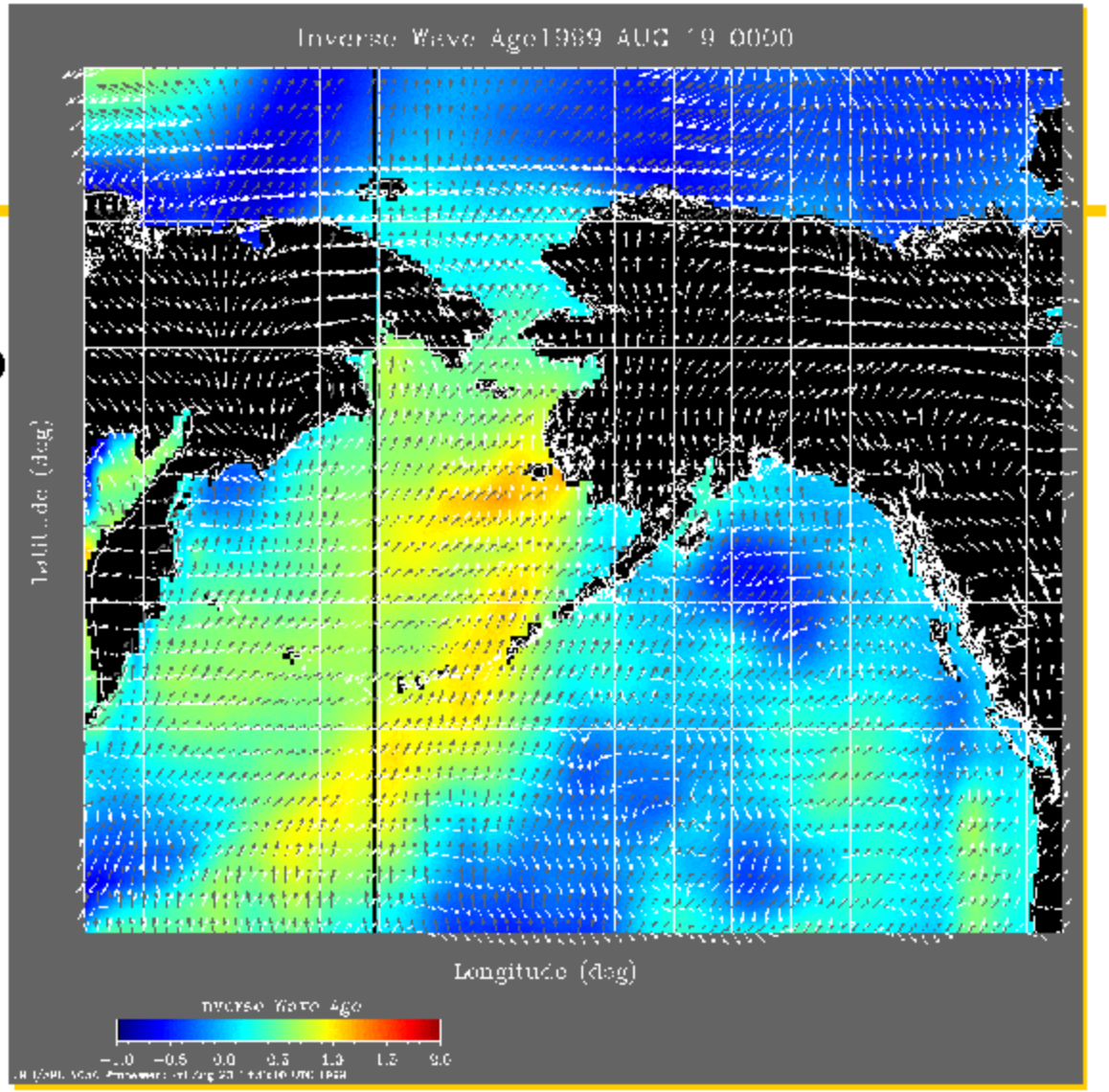
Model images: wave age

Wave age **is the ratio wind speed to wave phase speed. If the sea is newly generated, waves should be young, i.e. slower than the wind.**



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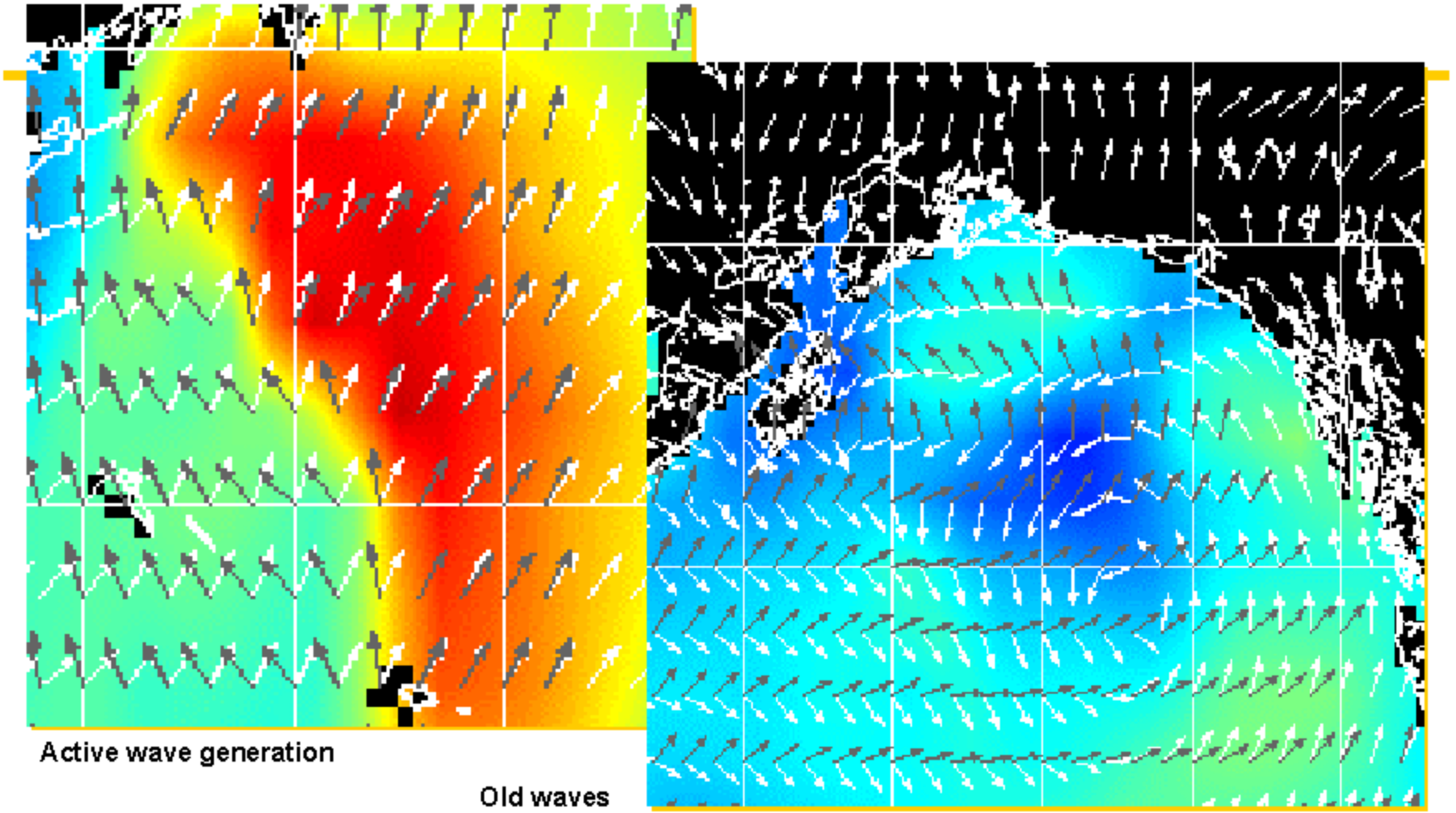
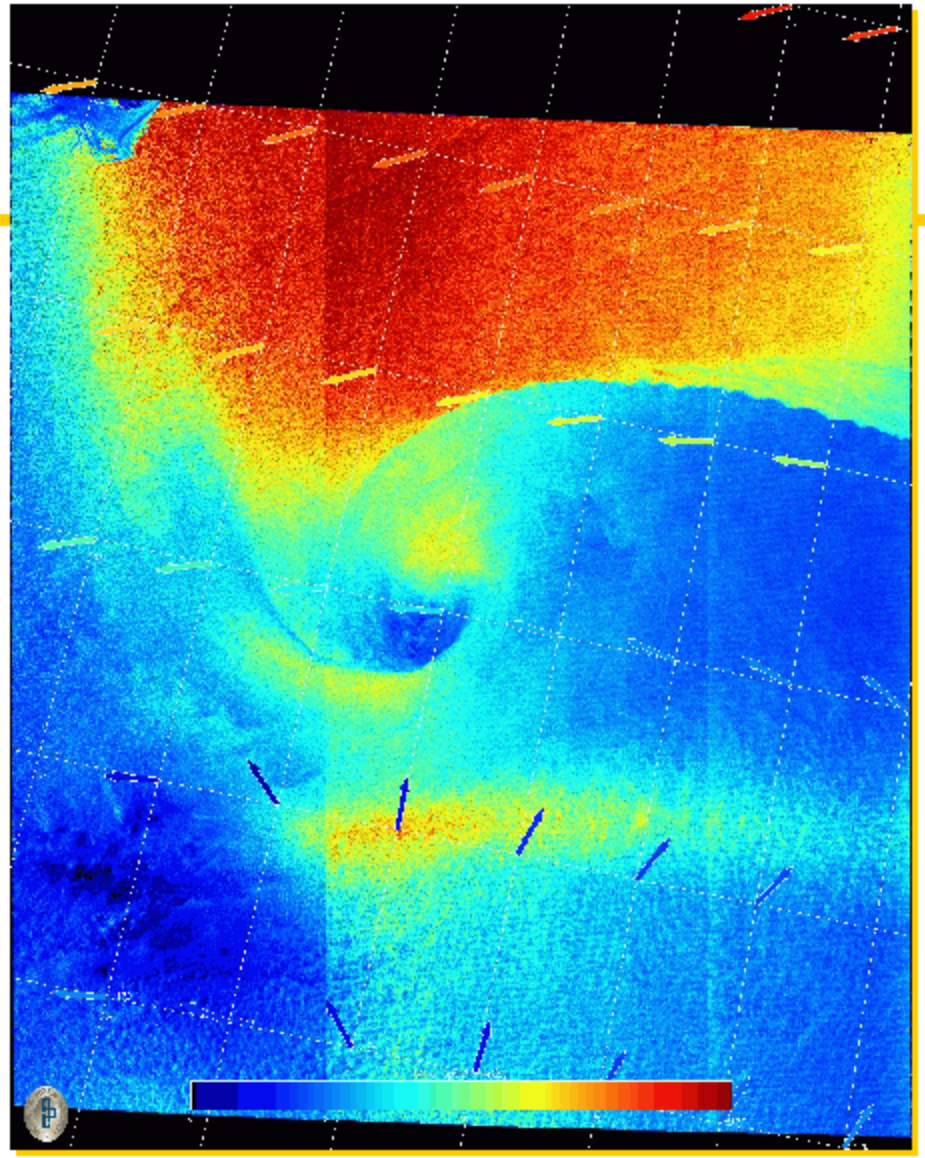
Wave age close-up



Anomalies: misplaced lows

In this case of a polar low, the SAR image indicates that the model slightly misplaced the position of the low.



1998 Feb 05, 06:02:27 Z

Anomalies: wind direction rotation

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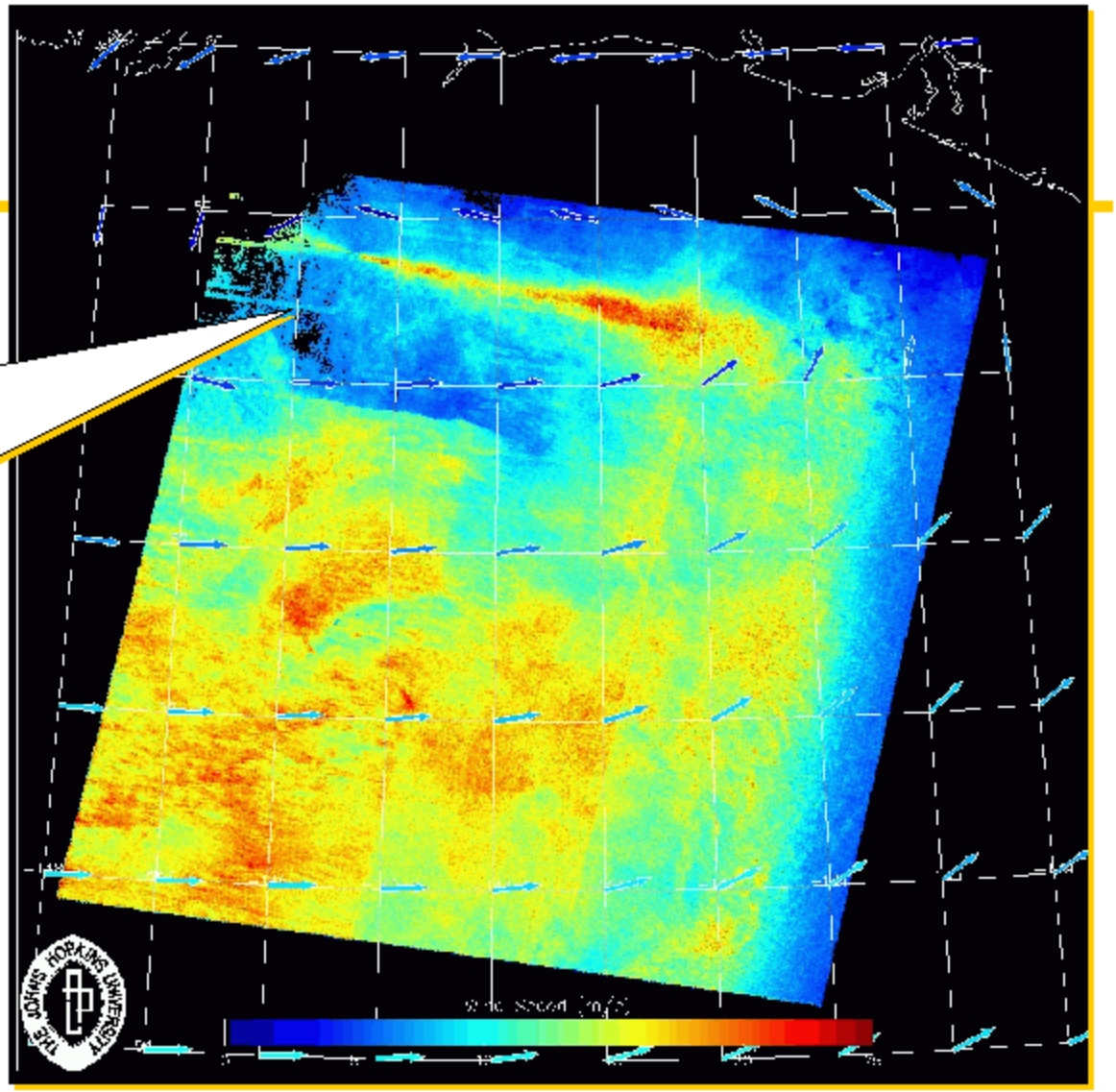
The rotation of wind direction can create apparent cross wind conditions that cause the wind speed retrieval to be overestimated.



1999 July 19, 15:55:53 Z

Anomalies: ice

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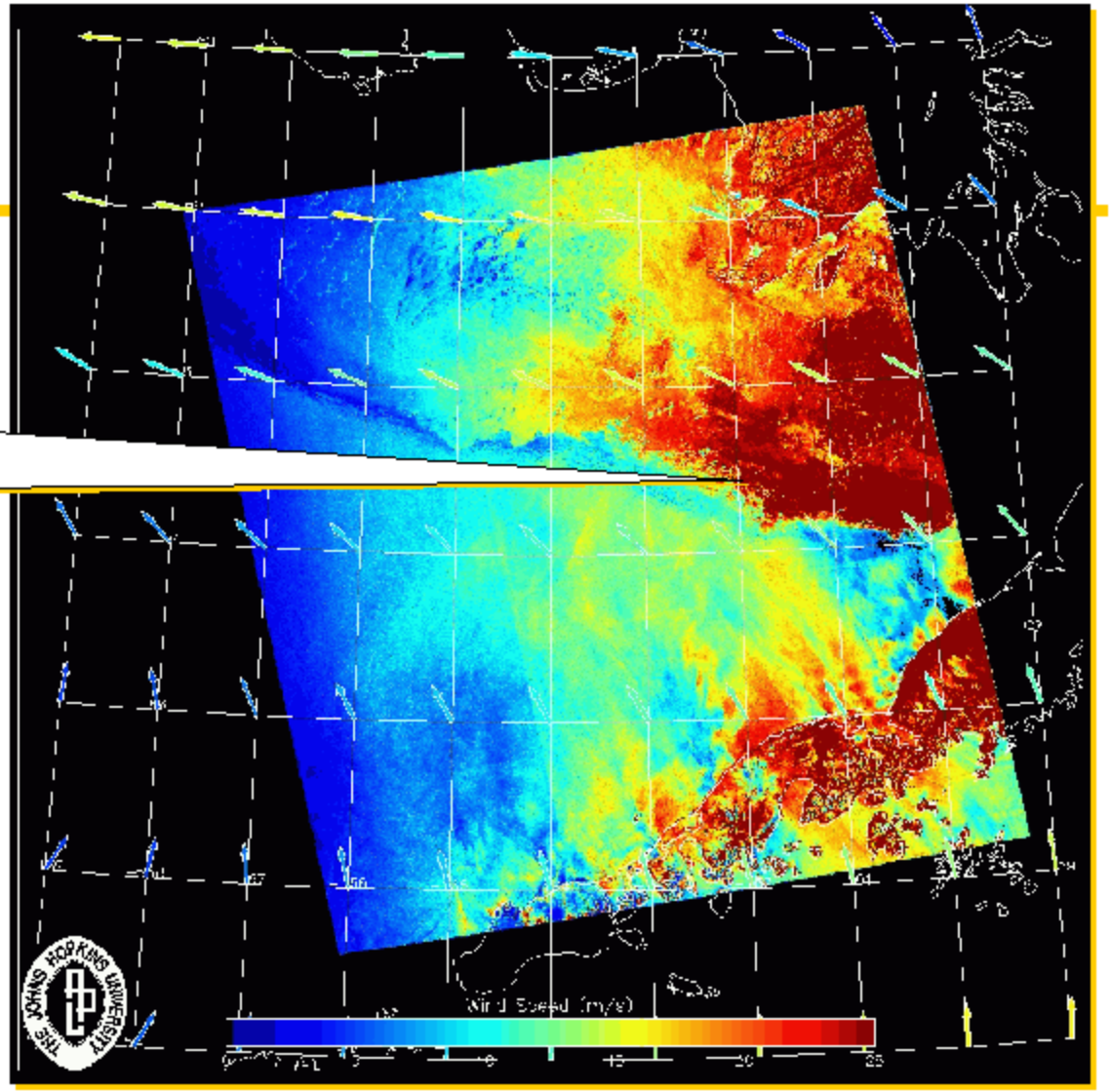
Ice usually has high cross section, perhaps with a sharp boundary.



1999 April 16, 16:34:04 Z

Anomalies: ice

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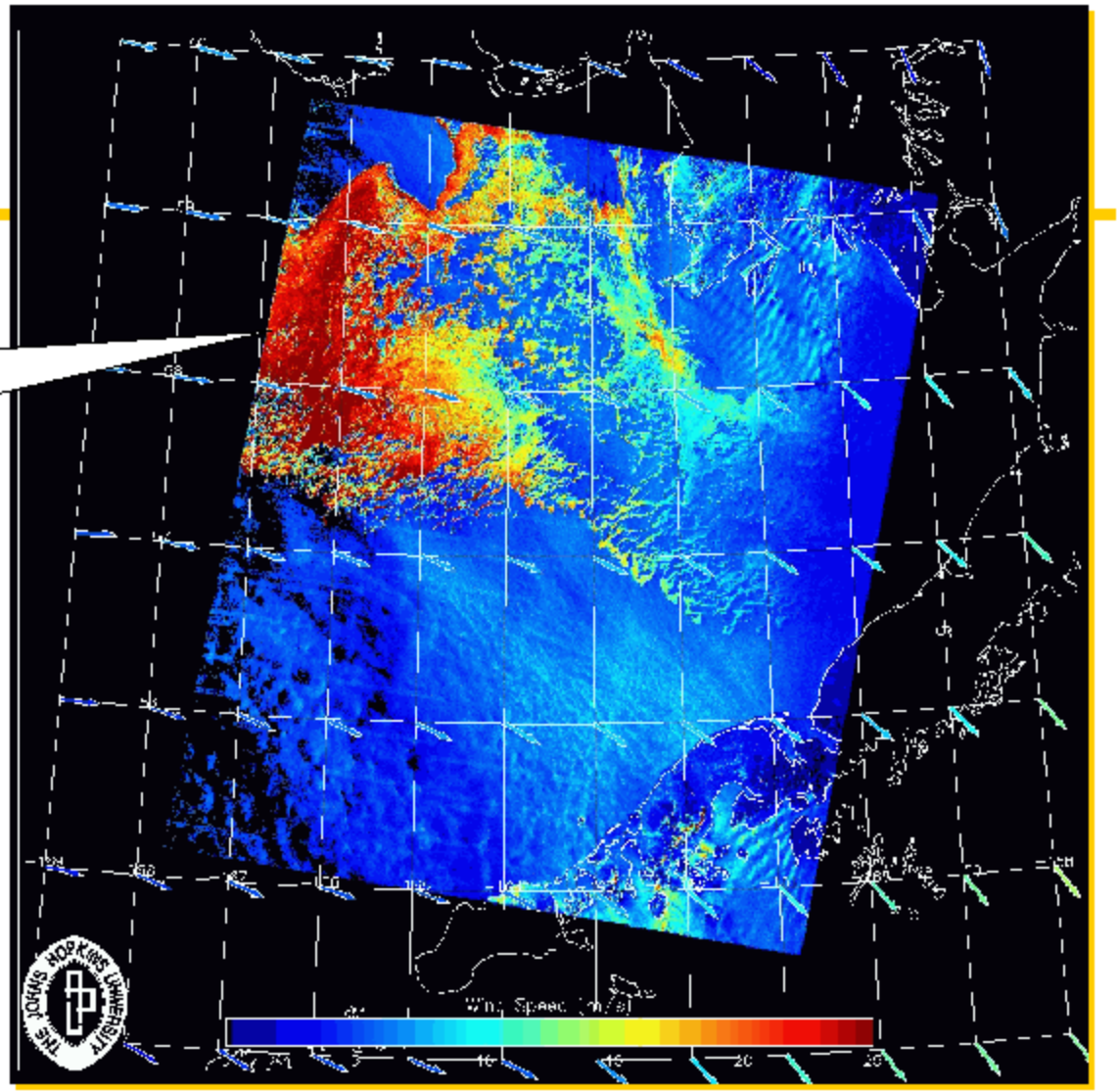

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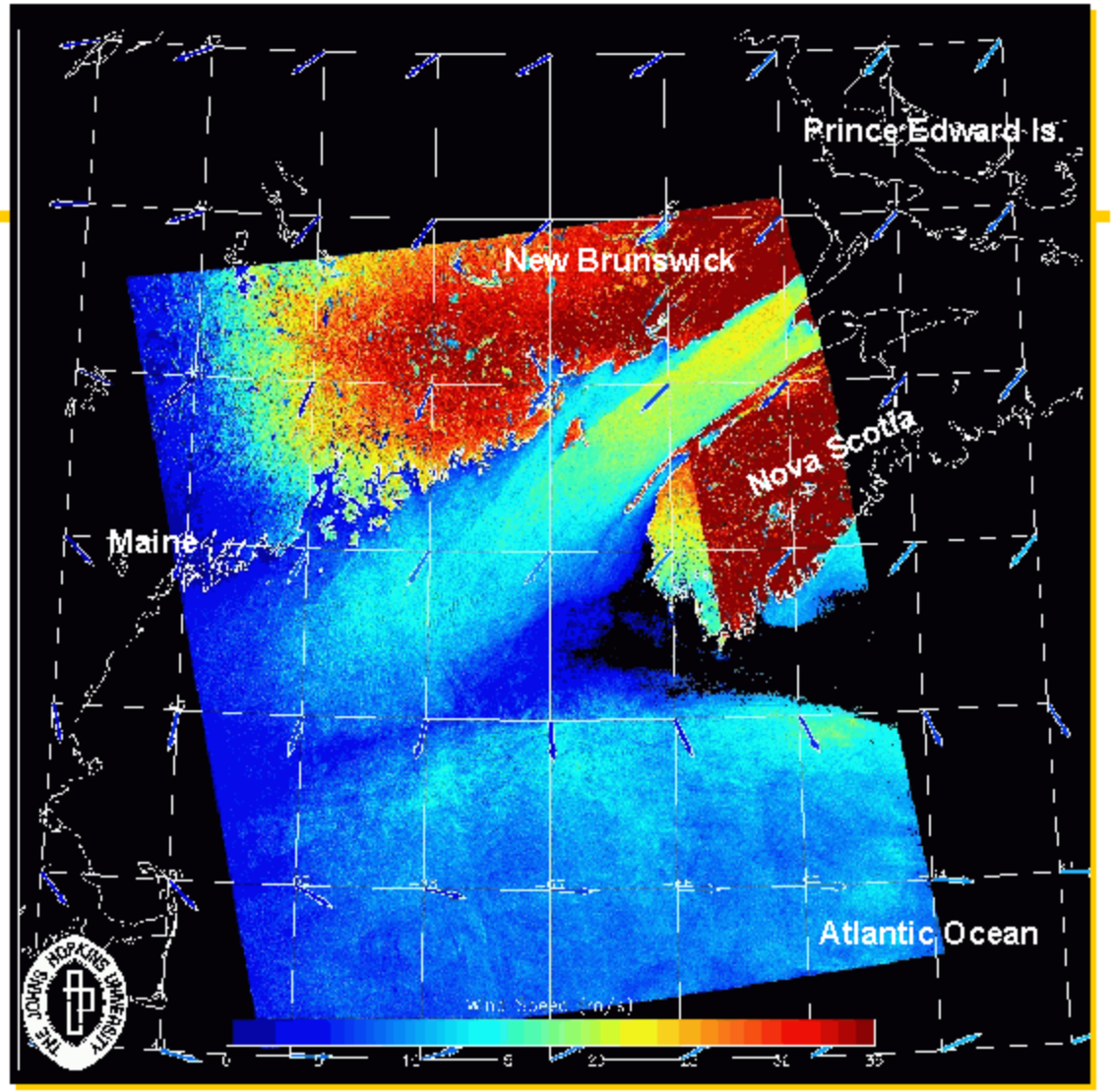
Localized high wind speed

High wind speed in the Bay of Fundy



1998 January 06, 22:22:05 Z

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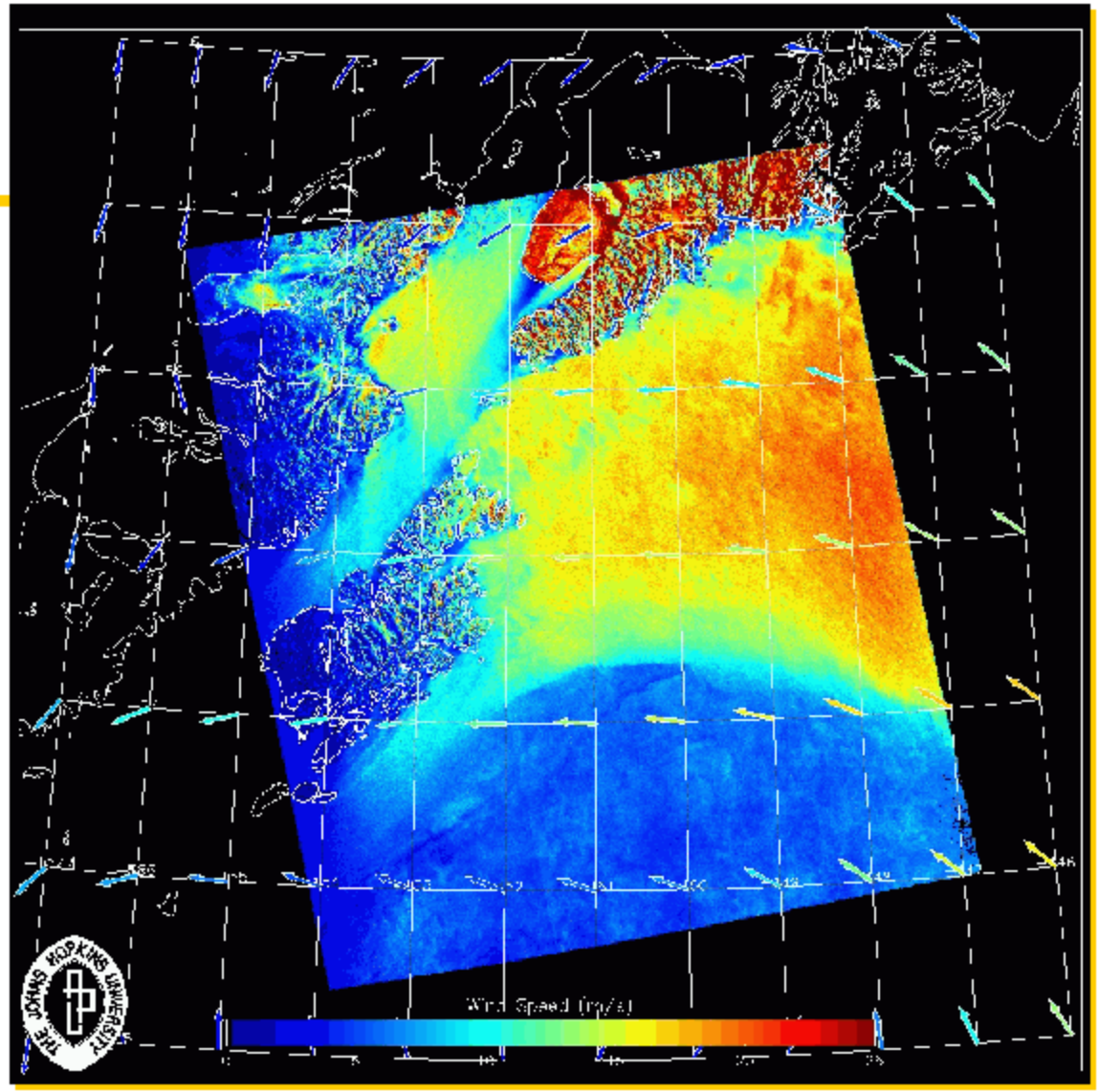
Model misplaces high wind area

Model misplaces high wind area but gives correct directions. SAR reveals high wind region.



1999 March 11, 03:53:51 Z

Hot off the presses

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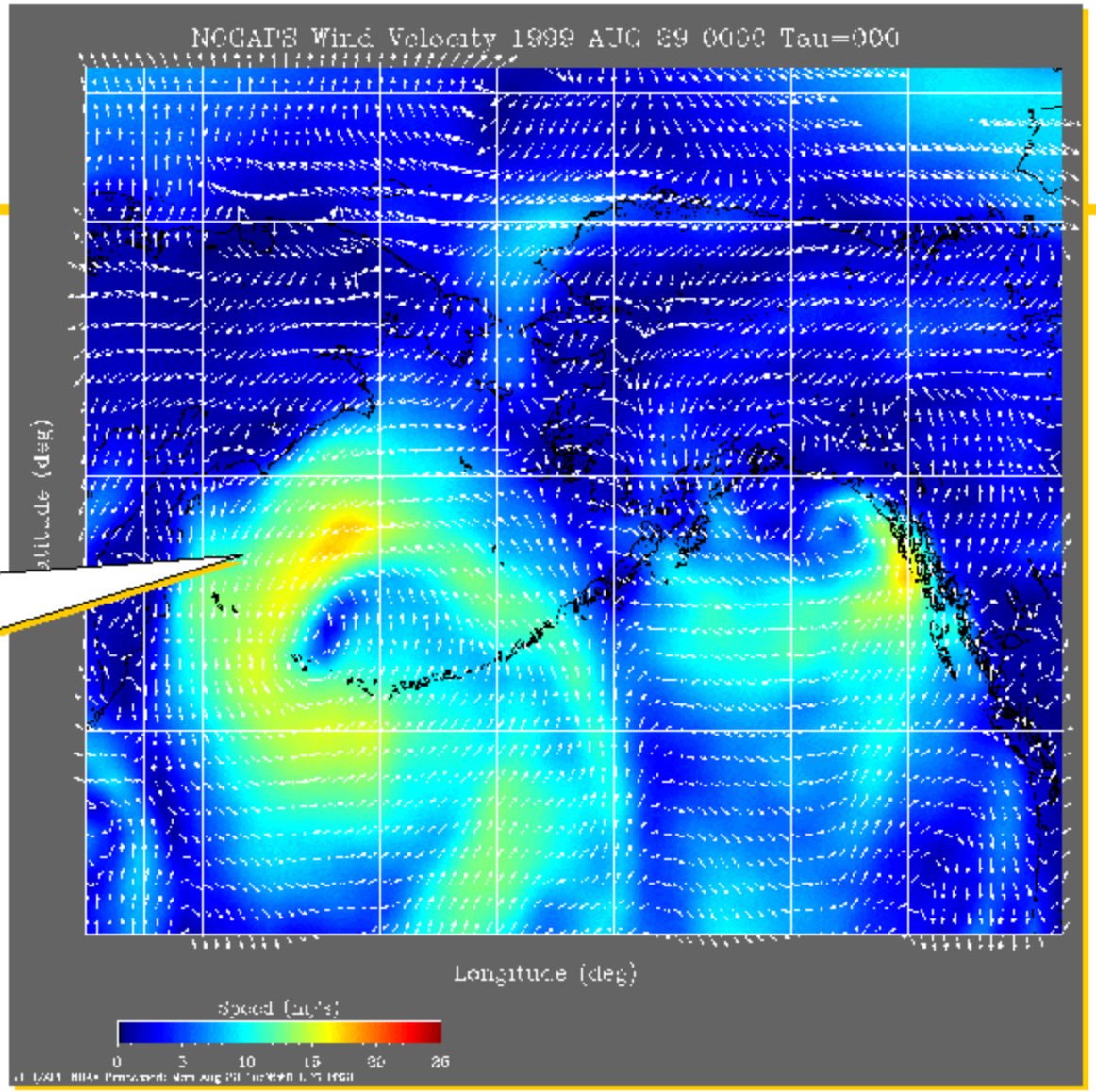

High wind area on 1999 Aug 29 00 Z as shown in NOGAPS nowcast.

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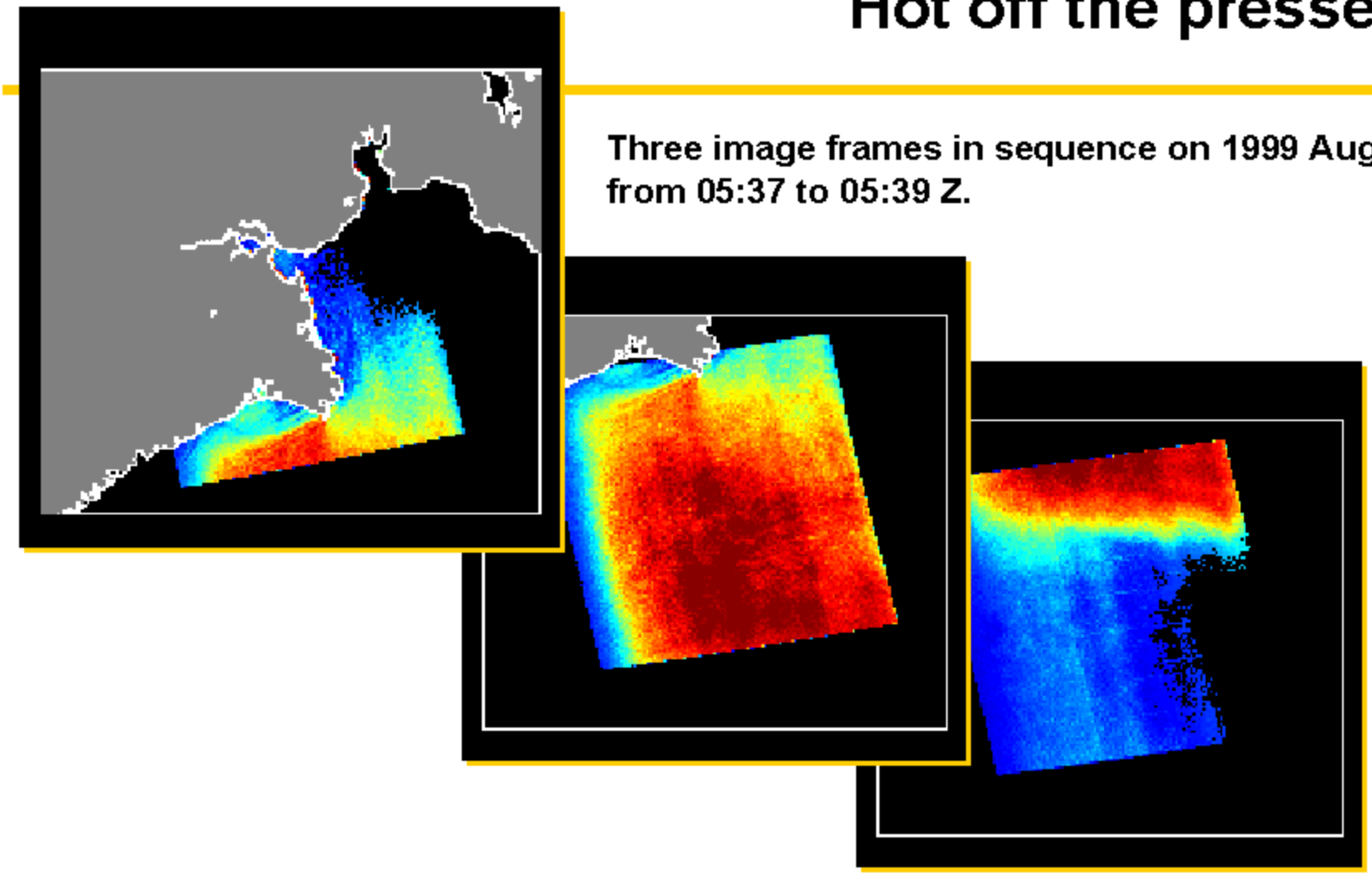
Hot off the presses

Three image frames in sequence on 1999 Aug 29 from 05:37 to 05:39 Z.



Hot off the presses

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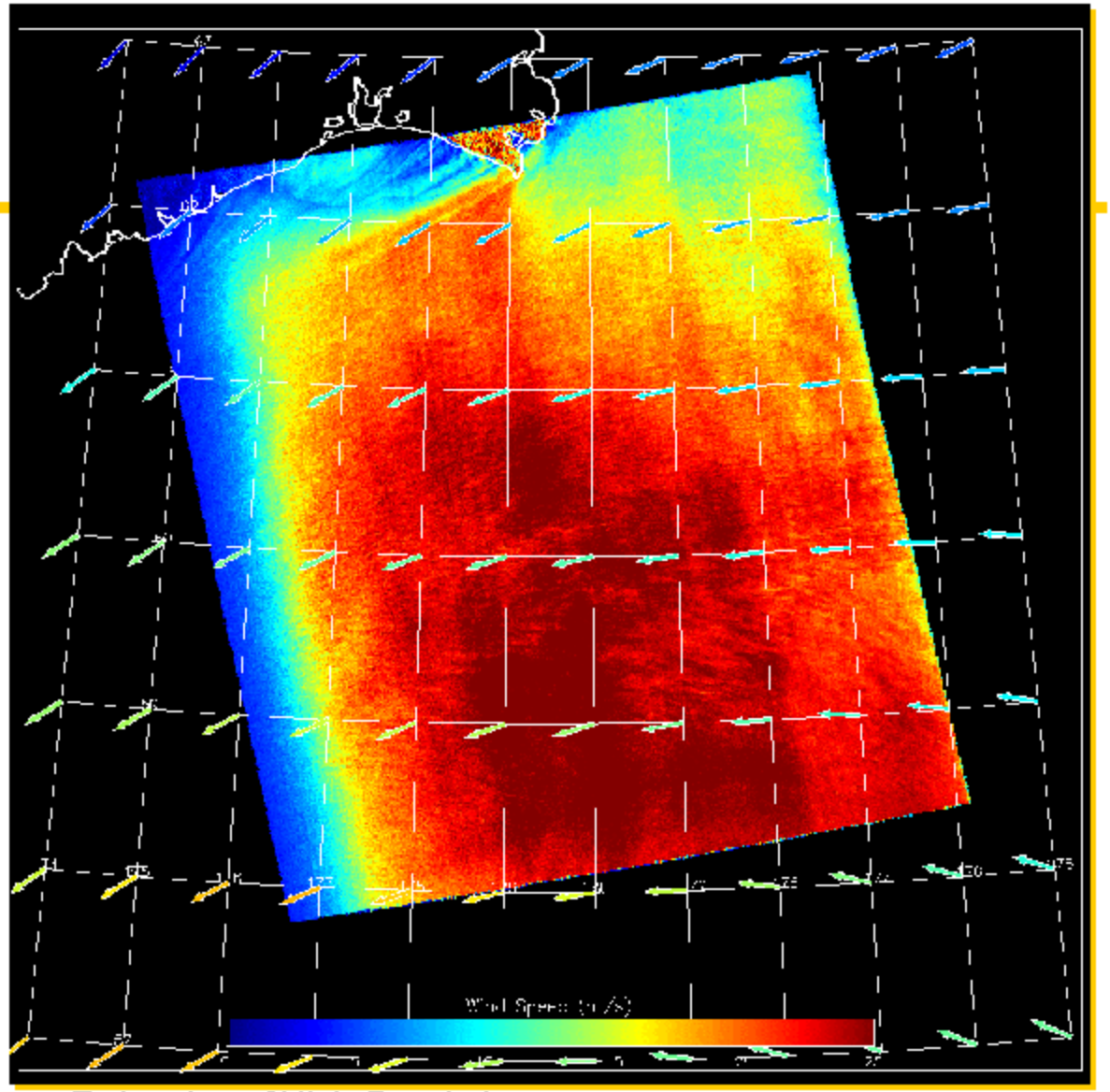
- Higher winds than predicted by the NOGAPS model.
- Land shadowing.
- Low response near range.



Validation

- A text file comparing wind speed from the NOGAPS model and the SAR.
  - If we assume that the model wind speeds are correct, "on average," then a comparison with SAR-derived winds should reveal systematic bias.
  - Large number of potential comparisons.
- Buoy data
  - Routinely stored.
  - Buoy data more accurate.
  - Fewer comparisons because of the lack of buoys.

Very hot off the presses

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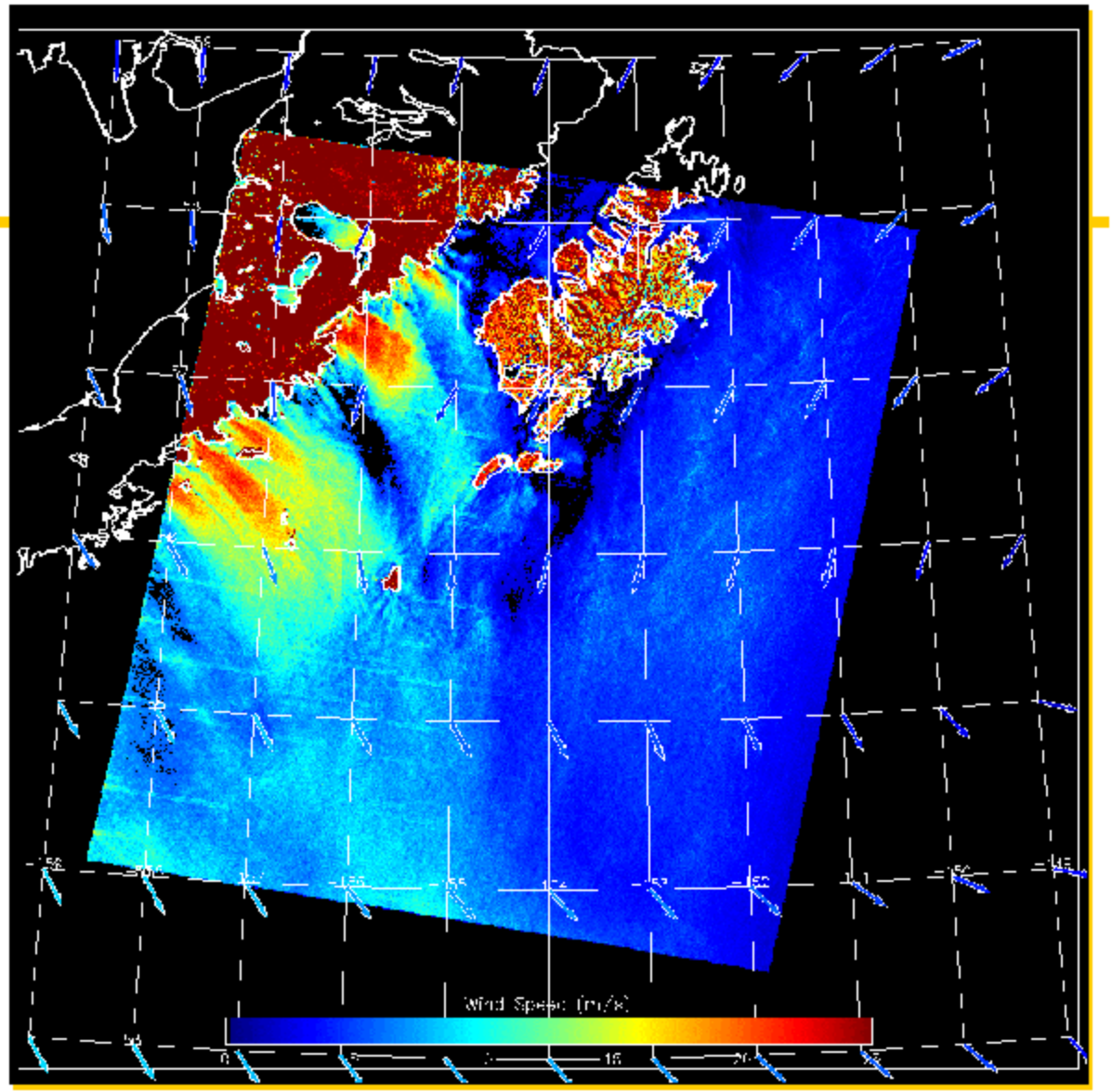
September 07, 1999 16:38 Z



Preliminary Comparisons

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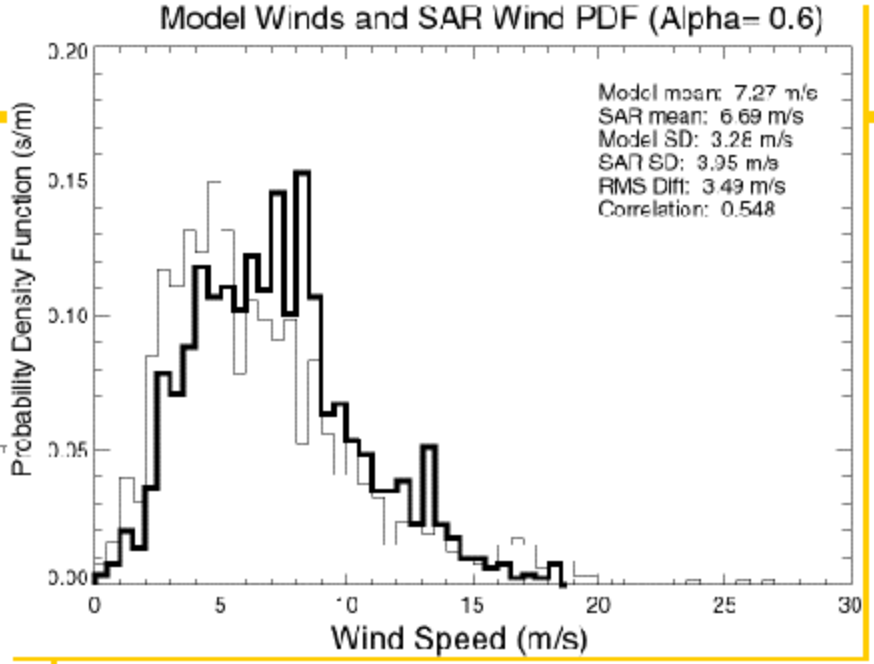
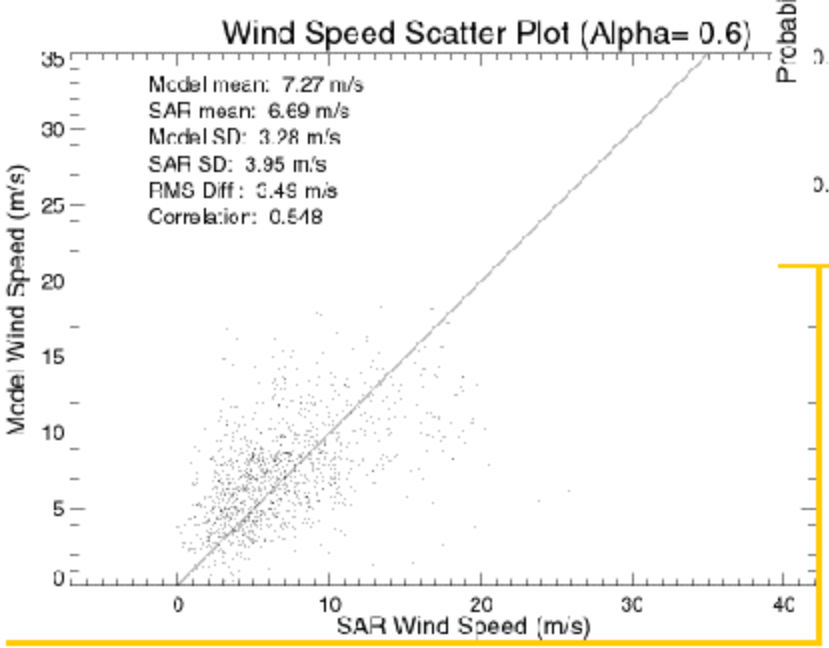
Probability Density





Scatter Plot

Conclusions

- Radar cross section is related to surface roughness at the radar wavelength.
  - Higher the wind the higher the RCS.
  - RCS decreases with nadir incidence angle.
  - RCS highest for upwind/downwind aspect.
  - RCS lowest for cross wind aspect.
- Need wind direction to estimate wind speed.
  - We use a model estimate of wind direction.
- Interpretation of requires being aware of ice areas and anomalies in wind direction

Conclusions

- The first year will help assess and improve accuracy of wind retrieval.
  - Comparison with model predictions.
  - Comparison with buoys.
  - *Feedback from users on utility:*
    - Accuracy
    - Timeliness
    - Presentation/Access
    - Resolution